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MULTISPECTRAL CHARACTERISTICS

OF CLOUDS OBSERVED BY LANDSAT 2

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AND RAINFALL OVER THE BRITISH ISLES  
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ERTS Follow-on Programme Study No. 2962A

Fourth Quarterly Report on  
Mesoscale Assessments of Cloud and Rainfall  
over the British Isles

by

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M.Sc., Ph.D., F.R.G.S., F.R.Met.S., F.B.I.S.

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## I INTRODUCTION

In our two previous reports attention was paid to the compilation of cloud photointerpretation keys for Landsat imagery so that the recognition of various cloud types might be put on a firm footing (Barrett and Grant, 1976a), and eyeball and machine-assisted comparisons were made between estimates of cloud cover imaged by Landsat and observed from the ground (Barrett and Grant, 1976b). This latter work included the development of an appropriate methodology, and the compilation of some initial results. In due course it is intended that these results should be supplemented by others for that portion of the study period for which imagery had not become available (generally February and March, 1976). Since we had not received our final consignments of images by mid-August 1976 the completion of that part of our exercise has still to be effected. Table 1 and Figure 1 indicate the frames received since the preparation of the Third Quarterly Report; Figure 2 displays the distribution through time of our entire archive of images as it stands at the time of writing.

It was thought convenient, whilst we were awaiting the remainder of the images for our study period, to experiment with a further section of our work which seeks to evaluate Landsat cloud images in comparison with those from other satellite families. This section is concerned with simultaneous analyses of data in all four Landsat multispectral sensor wavebands, leading to an appreciation of the suitability of the Landsat MSS wavebands for cloud analysis and identification. Many studies have considered the multispectral responses of Landsat-viewed surface-features; many more have considered the significance of multispectral data for differentiating both between and within classes of a wide variety of surface features (see e.g. NASA, 1975). However, we are unaware of detailed studies of the multispectral characteristics of Landsat-viewed clouds, though Danko (1974) addressed himself in part to this question.

Tabulation of Individual Frames  
(see also Table 2 in Barrett and Grant, 1975(b), Table 1 in Barrett and Grant 1976(a), and Table 1 in Barrett and Grant 1976 (b)).

DAY Since Launch	DATE (1975)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	CO-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2323	11 DECEMBER	4500	008 042 009 043	025 059 026 060	11:06:00	N 54:34	W 011:19
"	"	"			11:06:30	N 53:10	W 012:07
2338	26 DECEMBER	4709	061 133 062 134 063	097 169 098 170 099	10:49:10	N 53:08	W 007:53
"	"	"			10:49:30	N 51:43	W 008:36
"	"	"	135 064	171 100	10:50:00	N 50:18	W 009:17
"	"	"	136	172	10:50:20	N 48:53	W 009:56
1976							
2347	4 JANUARY	4834	229 255 230	242 268 243	09:58:10	N 50:11	E 003:33
"	"	"	256	269	09:58:40	N 48:46	E 002:54
2354	11 JANUARY	4932	008 068 009	038 098 039	10:37:00	N 54:18	W 004:24
"	"	"	069 010	099 040	10:37:30	N 52:54	W 005:09
"	"	"	070 011	100 041	10:37:50	N 51:30	W 005:51
"	"	"	071	101	10:38:20	N 50:06	W 006:32
2355	12 JANUARY	4946	006 MSG 007	037 099 038	10:42:50	N 54:19	W 005:50
"	"	"	MSG 008	100 039	10:43:10	N 52:55	W 006:35
"	"	"	MSG 009	101 040	10:43:40	N 51:31	W 007:18
"	"	"	MSG 010	102 041	10:44:00	N 50:07	W 007:58
"	"	"	MSG	103	10:44:30	N 48:42	W 008:37
2357	14 JANUARY	4974	066 096 067	081 111 082	10:55:30	N 50:10	W 010:48
"	"	"	097	112	10:55:50	N 48:45	W 011:27
2358	15 JANUARY	4988	010 038	024 052	11:01:40	N 48:44	W 012:53

DAY Since Launch	DATE (1976)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	CO-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2359	16 JANUARY	5002	167 199 168 200	183 215 184 216	11:06:30	N51:32	W013:01
"	"	"			11:07:00	N50:07	W013:42
2378	4 FEBRUARY	5267	028 070 029 071 030 072 031 073 032 074	049 091 050 092 051 093 052 094 053 095	11:09:50	N58:26	W010:29
"	"	"			11:10:20	N57:02	W011:23
"	"	"			11:10:40	N55:39	W012:15
"	"	"			11:11:10	N54:15	W013:03
"	"	"			11:11:30	N52:51	W013:48
2380	6 FEBRUARY	5295	102 144 103 145	123 165 124 166	11:21:00	N59:41	W012:30
"	"	"			11:21:20	N58:18	W013:28
2383	9 FEBRUARY	5336	059 099 060 100	079 119 080 120	09:57:40	N49:55	E003:22
"	"	"			09:58:10	N48:30	E002:43
2384	10 FEBRUARY	5350	072 110 073 111 074 112 075 113	091 129 092 130 093 131 094 132	10:02:40	N52:42	E003:17
"	"	"			10:03:00	N51:18	E002:35
"	"	"			10:03:30	N49:54	E001:56
"	"	"			10:03:50	N48:29	E001:18
2385	11 FEBRUARY	5364	092 138 093 139 094 140 095 141 096 142 097 143	115 161 116 162 117 163 118 164 119 165 120 166	10:07:30	N55:38	E003:30
"	"	"			10:07:50	N54:15	E002:43
"	"	"			10:08:20	N52:51	E001:58
"	"	"			10:08:40	N51:27	E001:15
"	"	"			10:09:10	N50:03	E000:34
"	"	"			10:09:30	N48:39	W000:05
2386	12 FEBRUARY	5378	122 190 123 191	156 224 157 225	10:12:20	N58:24	E003:48
"	"	"			10:12:40	N57:01	E002:54

DAY Since Launch	DATE (1976)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	CO-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2386	12 FEBRUARY	5378	124 192 125 193 126 194 127 195	158 226 159 227 160 228 161 229	10:13:10	N55:37	E002:03
"	"	"	126 194 127 195	160 228 161 229	10:13:30	N54:13	E001:16
"	"	"	126 194 127 195	160 228 161 229	10:14:00	N52:49	E000:31
"	"	"	127 195 128 196 MSG 197	161 229 162 230 MSG 231	10:14:20	N51:25	W000:11
"	"	"	128 196 MSG 197	162 230 MSG 231	10:14:50	N50:01	W000:51
"	"	"	MSG 197	MSG 231	10:15:10	N48:37	W001:30
2387	13 FEBRUARY	5392	020 064 021 065 022 066 209 MSG 210 256 211 257 212 258 213 259	042 086 043 087 044 088 MSG MSG 233 279 234 280 235 281 236 282	10:17:40	N59:48	E003:19
"	"	"	021 065 022 066 209 MSG 210 256 211 257 212 258 213 259	043 087 044 088 MSG MSG 233 279 234 280 235 281 236 282	10:18:00	N58:25	E002:22
"	"	"	022 066 209 MSG 210 256 211 257 212 258 213 259	044 088 MSG MSG 233 279 234 280 235 281 236 282	10:18:30	N57:02	E001:29
"	"	"	209 MSG 210 256 211 257 212 258 213 259	MSG MSG 233 279 234 280 235 281 236 282	10:18:50	N55:39	E000:38
"	"	"	210 256 211 257 212 258 213 259	233 279 234 280 235 281 236 282	10:19:20	N54:15	W000:09
"	"	"	211 257 212 258 213 259	234 280 235 281 236 282	10:19:40	N52:51	W000:54
"	"	"	212 258 213 259	235 281 236 282	10:20:10	N51:28	W001:36
"	"	"	213 259	236 282	10:20:30	N50:04	W002:16
2388	14 FEBRUARY	5406	078 122 079 123 080 124 081 125 082 126 083 127 084 128 085 129 086 130	100 144 101 145 102 146 103 147 104 148 105 149 106 150 107 151 108 152	10:23:20	N59:47	E001:54
"	"	"	079 123 080 124 081 125 082 126 083 127 084 128 085 129 086 130	101 145 102 146 103 147 104 148 105 149 106 150 107 151 108 152	10:23:40	N58:24	E000:57
"	"	"	080 124 081 125 082 126 083 127 084 128 085 129 086 130	102 146 103 147 104 148 105 149 106 150 107 151 108 152	10:24:10	N57:01	E000:03
"	"	"	081 125 082 126 083 127 084 128 085 129 086 130	103 147 104 148 105 149 106 150 107 151 108 152	10:24:30	N55:38	W000:47
"	"	"	082 126 083 127 084 128 085 129 086 130	104 148 105 149 106 150 107 151 108 152	10:25:00	N54:14	W001:35
"	"	"	083 127 084 128 085 129 086 130	105 149 106 150 107 151 108 152	10:25:20	N52:50	W002:20
"	"	"	084 128 085 129 086 130	106 150 107 151 108 152	10:25:50	N51:27	W003:03
"	"	"	085 129 086 130	107 151 108 152	10:26:10	N50:03	W003:43
"	"	"	086 130	108 152	10:26:40	N48:39	W004:22
2389	15 FEBRUARY	5420	024 082 025 083 001 055	053 111 054 112 028 082	10:29:00	N59:46	E000:28
"	"	"	025 083 001 055	054 112 028 082	10:29:30	N58:24	W000:30
"	"	"	001 055	028 082	10:29:50	N57:01	W001:24



DAY Since Launch	DATE (1976)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	CO-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2389	15 FEBRUARY	5420	002 056 003	029 083 030	10:30:20	N55:37	W002:14
"	"	"	057	084	10:30:40	N54:14	W003:02
"	"	"	004 058	031 085	10:31:10	N52:50	W003:47
"	"	"	005 059	032 086	10:31:30	N51:26	W004:30
"	"	"	006 060	033 087	10:32:00	N50:02	W005:10
"	"	"	007 061	034 088	10:32:20	N48:38	W005:49
2391	17 FEBRUARY	5448	001 043	022 064	10:40:30	N59:45	W002:23
"	"	"	002 044	023 065	10:40:50	N58:23	W003:21
"	"	"	277 MSG	MSG MSG	10:41:20	N57:00	W004:14
"	"	"	278 320	299 341	10:41:40	N55:36	W005:05
"	"	"	279 321	300 342	10:42:10	N54:13	W005:52
"	"	"	280 322	301 343	10:42:30	N52:49	W006:37
"	"	"	281 323	302 344	10:43:00	N51:25	W007:19
"	"	"	282 324	303 345	10:43:20	N50:00	W007:59
"	"	"	283 325	304 346	10:43:50	N48:36	W008:38
2392	18 FEBRUARY	5462	014 056 015	035 077 036	10:46:10	N59:50	W003:49
"	"	"	057 016	078 037	10:46:30	N58:28	W004:47
"	"	"	058 017	079 038	10:47:00	N57:06	W005:40
"	"	"	059 018	080 039	10:47:20	N55:42	W006:30
"	"	"	060 019	081 040	10:47:50	N54:18	W007:17
"	"	"	061 020	082 041	10:48:10	N52:54	W008:02
"	"	"	062 001	083 031	10:48:40	N51:30	W008:45
"	"	"	MSG	MSG	10:49:30	N48:42	W010:04
2393	19 FEBRUARY	5476	001 045	023 067	10:51:50	N59:50	W005:15
"	"	"	002 046	024 068	10:52:20	N58:28	W006:12
"	"	"	003 047	025 069	10:52:40	N57:04	W007:06

DAY Since Launch	DATE (1976)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	CO-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2393	19 FEBRUARY	5476	004 047 005	026 070 027	10:53:10	N55:41	W007:57
"	"	"	048 006	071 028	10:53:30	N54:17	W008:44
"	"	"	049 007	072 029	10:54:00	N52:52	W009:28
"	"	"	050 008	073 030	10:54:20	N51:29	W010:10
"	"	"	051 009	074 031	10:54:50	N50:05	W010:51
"	"	"	052	075	10:55:10	N48:40	W011:29
2394	20 FEBRUARY	5490	288 328 289	308 348 309	10:57:40	N59:50	W006:39
"	"	"	329 290	349 310	10:58:00	N58:27	W007:37
"	"	"	330 291	350 311	10:58:30	N57:04	W008:32
"	"	"	331 292	351 312	10:58:50	N55:41	W009:23
"	"	"	332 293	352 313	10:59:20	N54:17	W010:11
"	"	"	333 294	353 314	10:59:40	N52:53	W010:56
"	"	"	334 295	354 315	11:00:10	N51:29	W011:39
"	"	"	335 296	355 316	11:00:30	N50:05	W012:19
"	"	"	336	356	11:01:00	N48:41	W012:57
2395	21 FEBRUARY	5504	015 065 016	040 090 041	11:03:20	N59:51	W008:05
"	"	"	066 017	091 042	11:03:40	N58:29	W009:03
"	"	"	067 018	092 043	11:04:10	N57:07	W009:57
"	"	"	068 019	093 044	11:04:30	N55:43	W010:48
"	"	"	069 020	094 045	11:05:00	N54:19	W011:35
"	"	"	070 021	095 046	11:05:20	N52:56	W012:20
"	"	"	071 022	096 047	11:05:50	N51:32	W013:03
"	"	"	072	097	11:06:10	N58:08	W013:43
2401	27 FEBRUARY	5587	008 044 009	026 062 027	09:57:10	N50:07	E003:28
"	"	"	045	063	09:57:40	N48:42	E002:50

DAY Since Launch	DATE (1976)	ORBIT NUMBER	Frame Numbers		TIME H : M : S	Co-ORDS OF CENTRE	
			4 6	5 7		LATITUDE	LONGITUDE
2402	28 FEBRUARY	5601	015 057 016 058 018 060	036 078 037 079 039 081	10:02:10	NS2:54	E003:24
"	"	"			10:02:30	NS1:30	E002:42
"	"	"			10:03:20	N48:42	E001:23
2403	29 FEBRUARY	5615	005 031 006 032 007 033 008 034 009 035 010 036	018 044 019 045 020 046 021 047 022 048 023 049	10:07:00	NS5:43	E003:30
"	"	"			10:07:20	NS4:20	E002:43
"	"	"			10:07:50	NS2:56	E001:58
"	"	"			10:08:10	NS1:32	E001:16
"	"	"			10:08:40	NS0:08	E000:36
"	"	"			10:09:00	N48:43	W000:02
2422	19 MARCH	5880	012 068 013 069 014 070	040 096 041 097 042 098	10:13:00	NS3:00	E000:36
"	"	"			10:13:20	NS1:36	W000:06
"	"	"			10:13:50	NS0:13	W000:47
2423	20 MARCH	5894	MSG 051	027 075	10:19:30	NS0:14	W002:11
2424	21 MARCH	5908	003 031 004 032 005 033	017 045 018 046 019 047	10:24:50	NS1:35	W002:58
"	"	"			10:25:10	NS0:11	W003:38
"	"	"			10:25:40	N48:47	W004:17
2425	22 MARCH	5922	168 236 169 237 170 238 171 239 172 240 173 241	202 270 203 271 204 272 205 273 206 274 207 275	10:29:10	NS5:48	W002:10
"	"	"			10:29:40	NS4:25	W002:57
"	"	"			10:30:00	NS3:01	W003:42
"	"	"			10:30:30	NS1:37	W004:25
"	"	"			10:30:50	NS0:13	W005:05
"	"	"			10:31:20	N48:48	W005:43
2426	23 MARCH	5936	078 122	100 144	10:34:30	NS7:14	W002:43
2427	24 MARCH	5950	012 MSG	036 084	10:39:50	NS8:39	W003:15

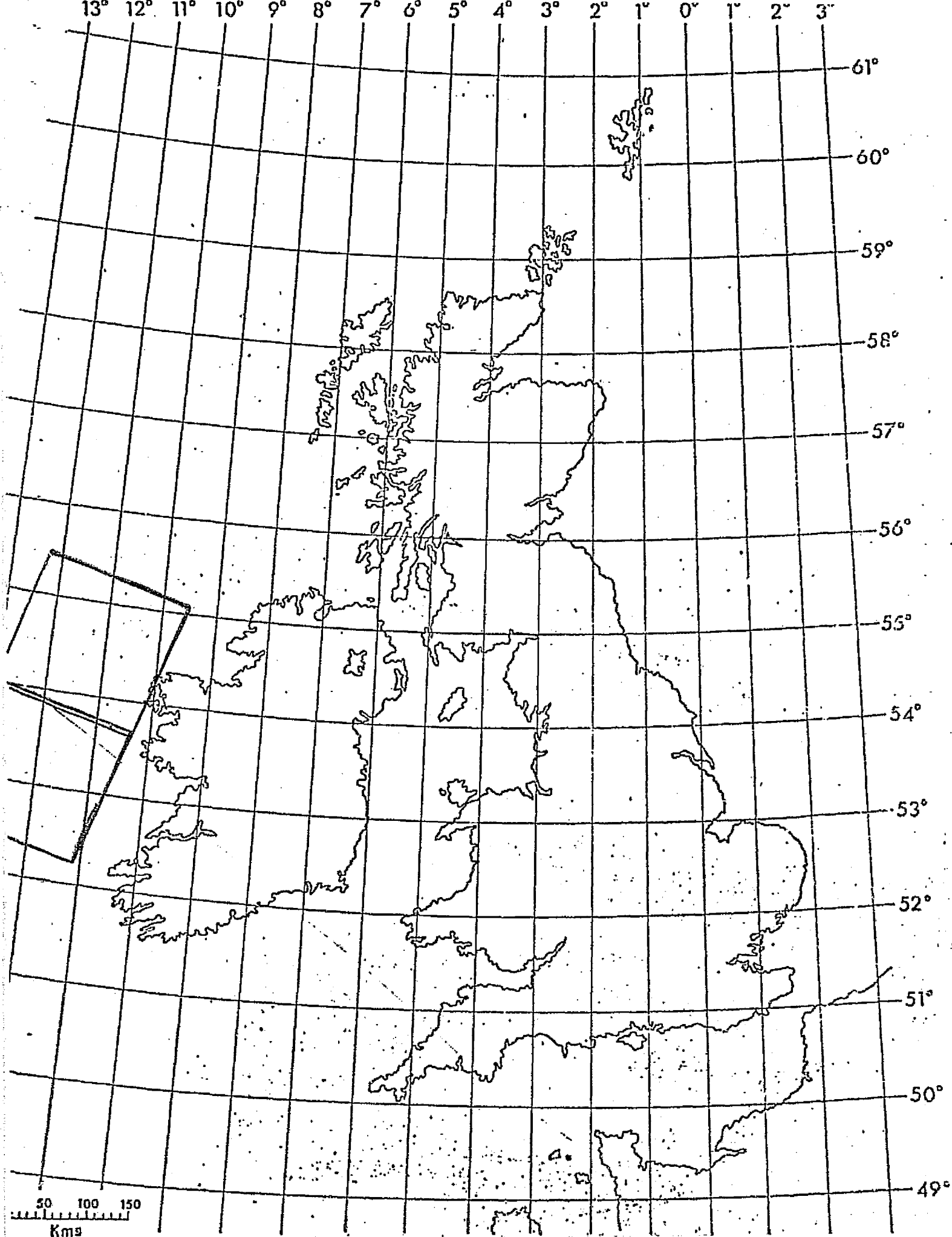


Fig. 1(a): Landsat coverage of the British Isles, Cycle 17,  
29th November - 16th December, 1975.

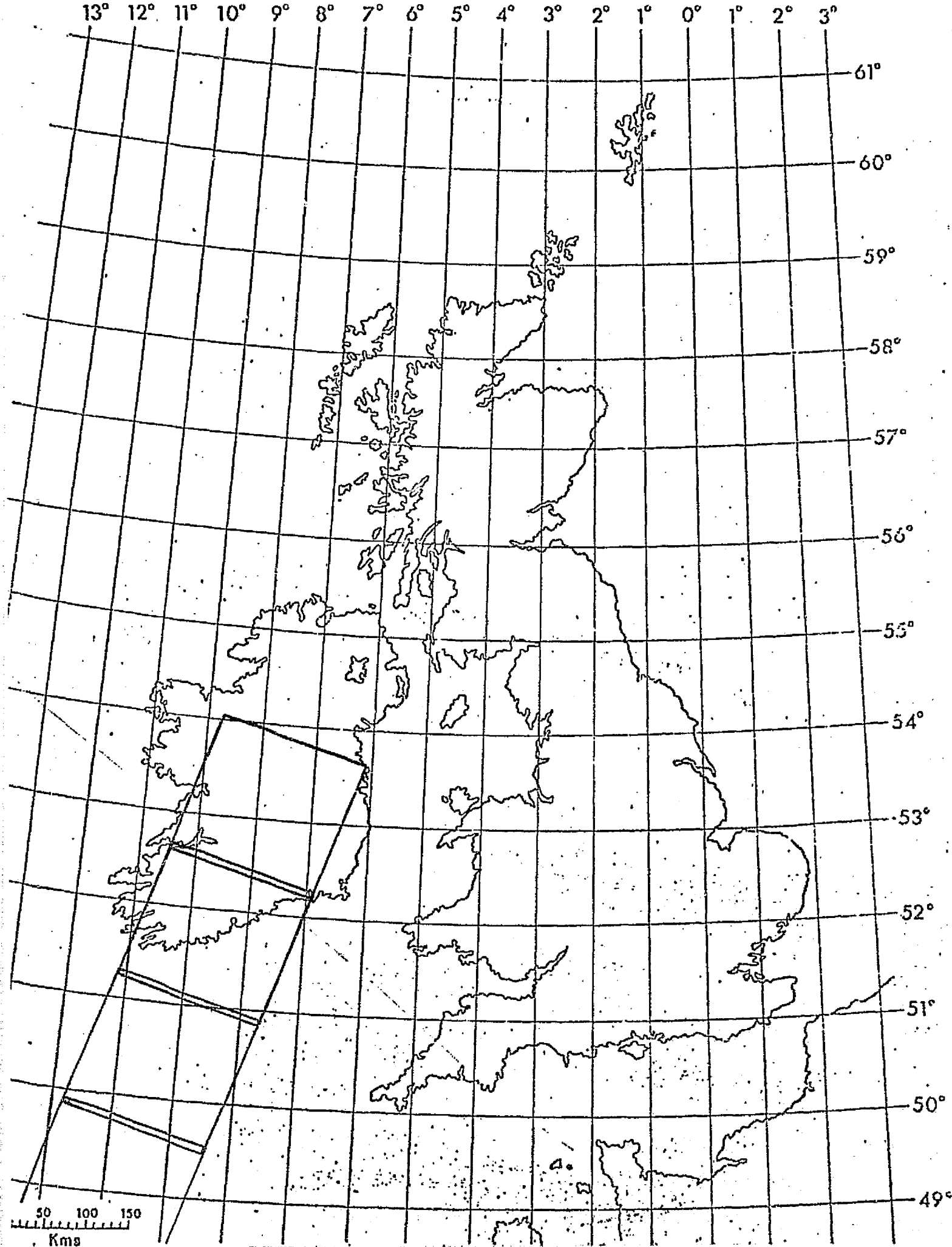


Fig. 1(b): Landsat coverage of the British Isles, Cycle 18,  
17th December, 1975 - 3rd January, 1976.

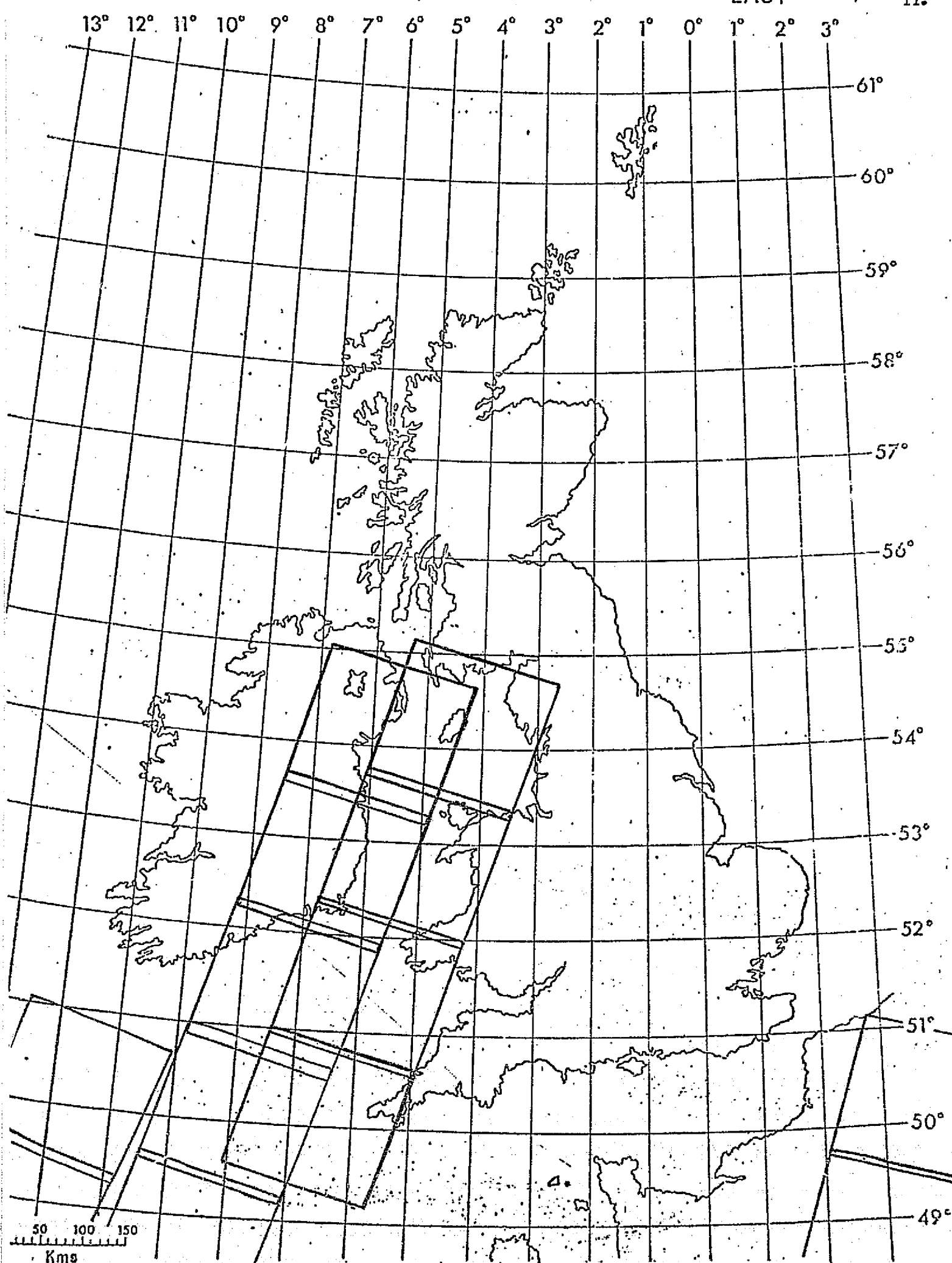


Fig. 1(c): Landsat coverage of the British Isles, Cycle 19,  
4th January, 1976 - 21st January, 1976.

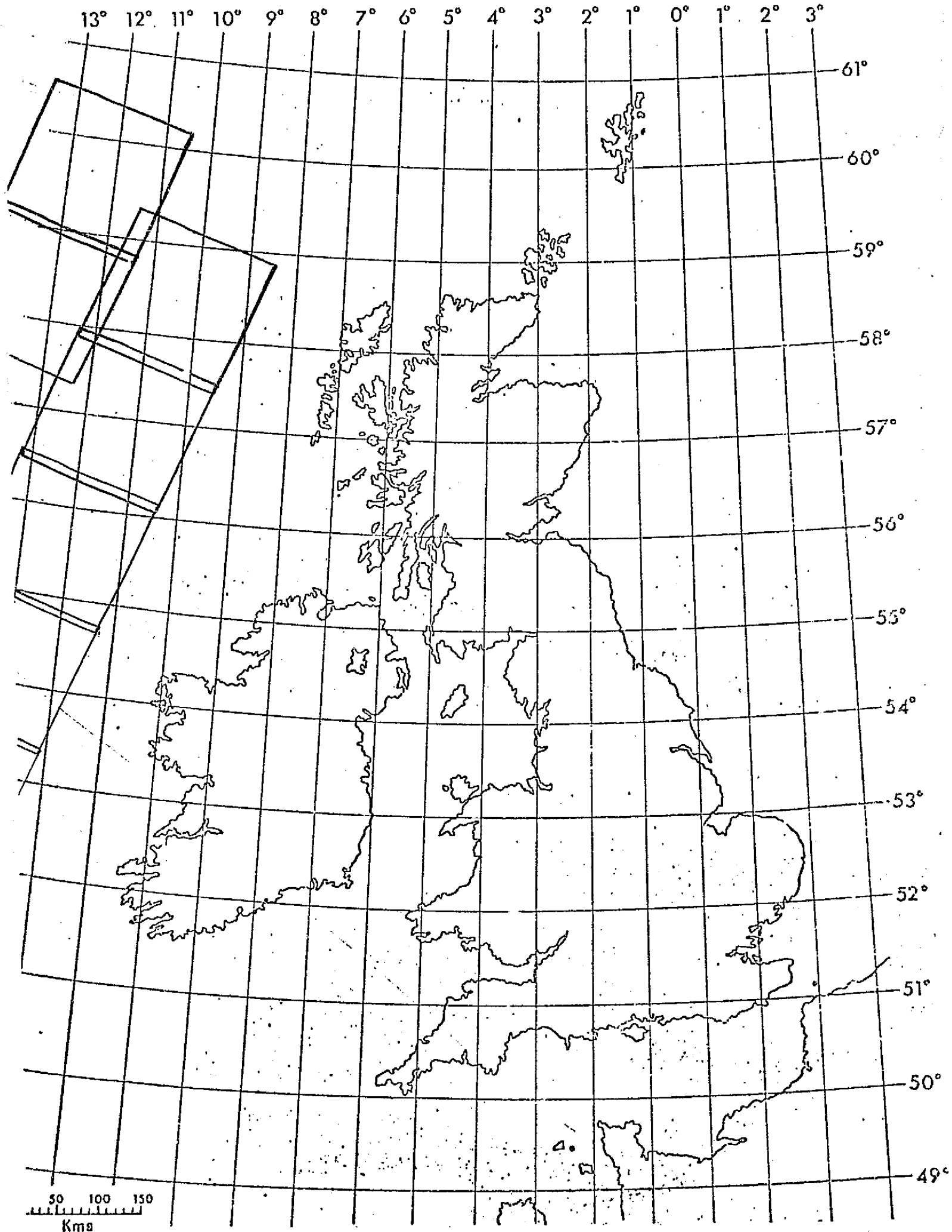


Fig. 1(d): Landsat coverage of the British Isles, Cycle 20,  
22nd January - 8th February, 1976.

REPRODUCTION OF THE  
ORIGINAL PAGE IS POOR

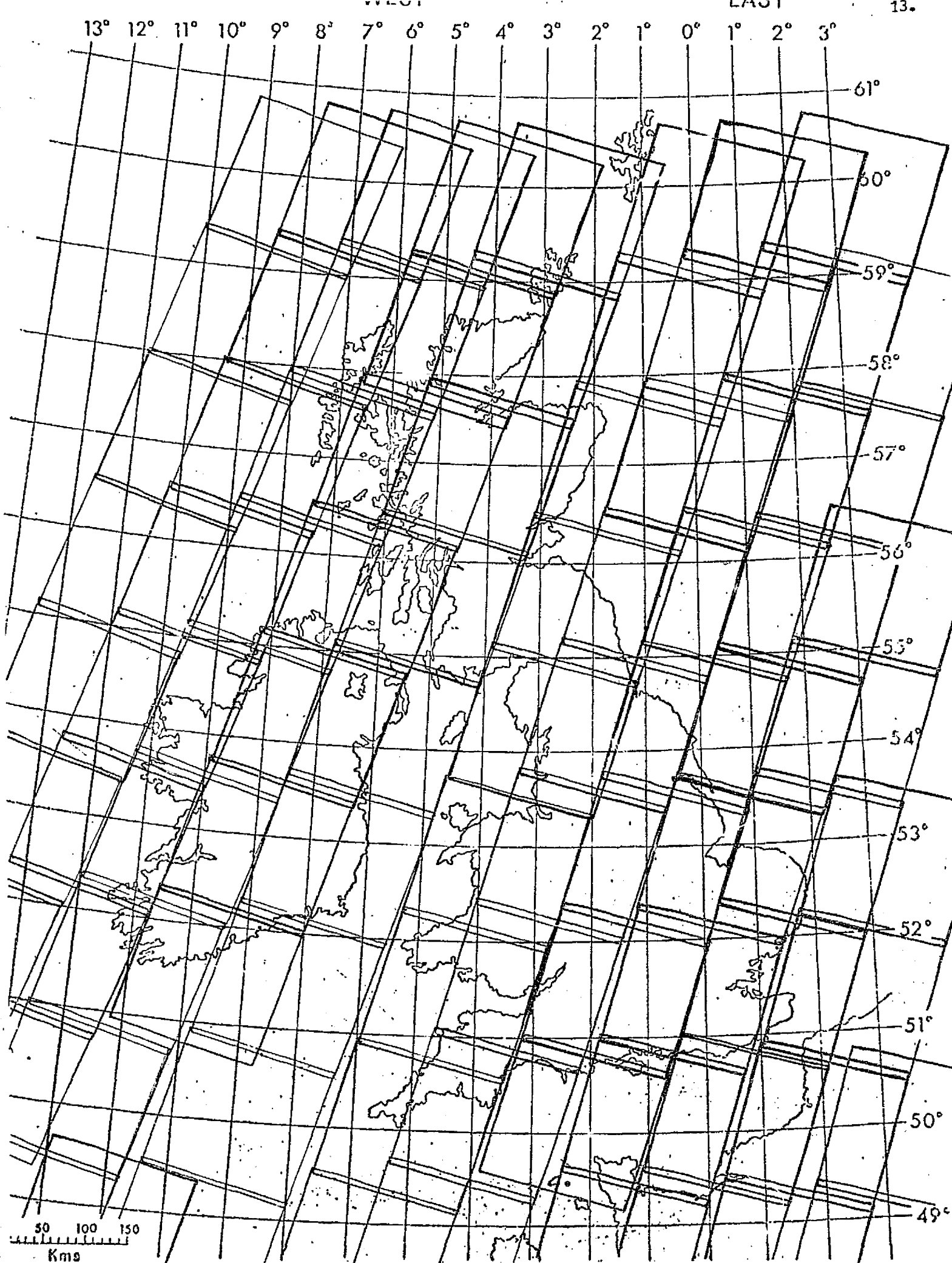


Fig. 1(e): Landsat coverage of the British Isles, Cycle 21,  
9th February - 26th February, 1976.



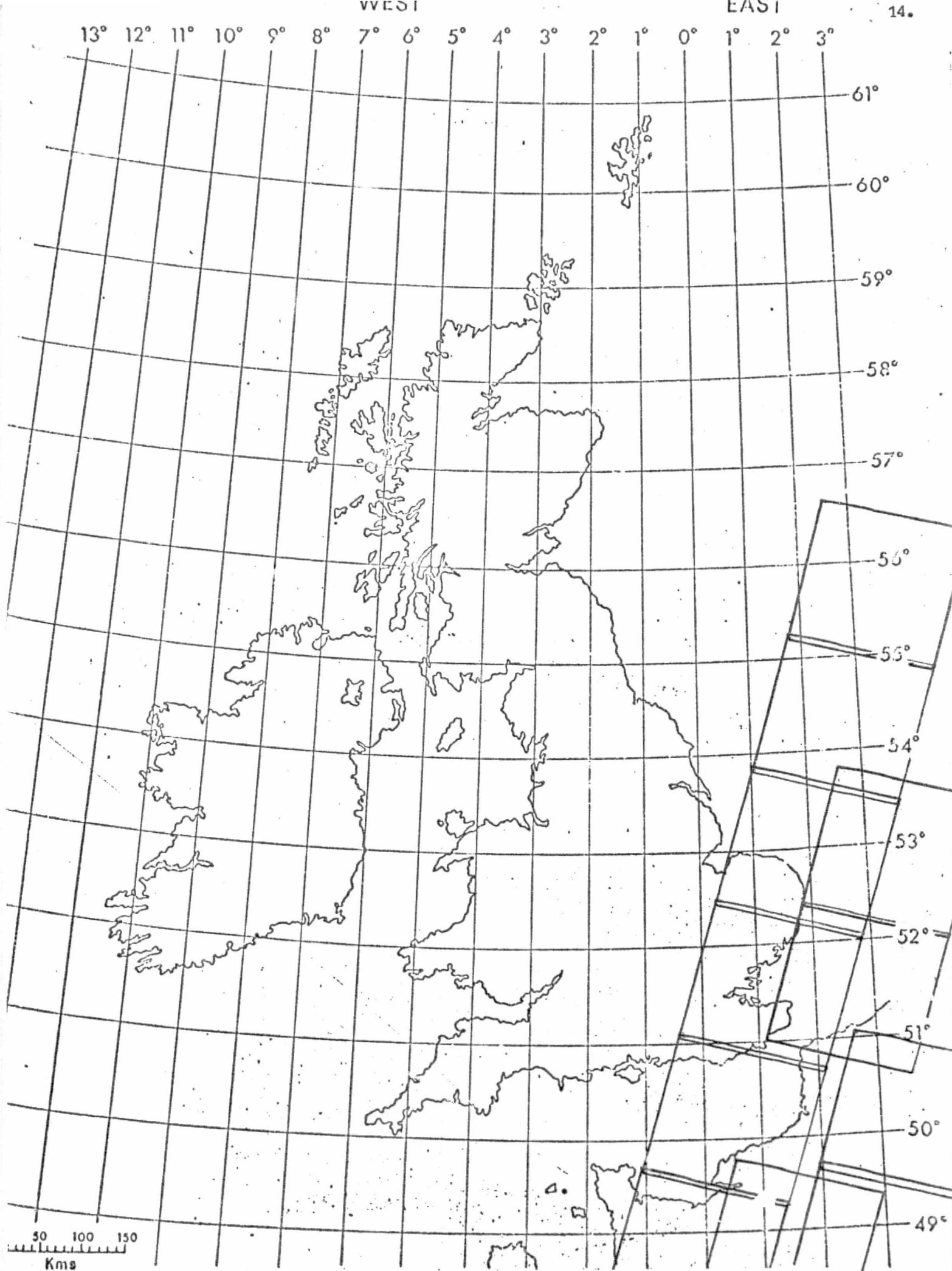


Fig. 1(f): Landsat coverage of the British Isles, Cycle 22,  
27th February - 15th March, 1976.

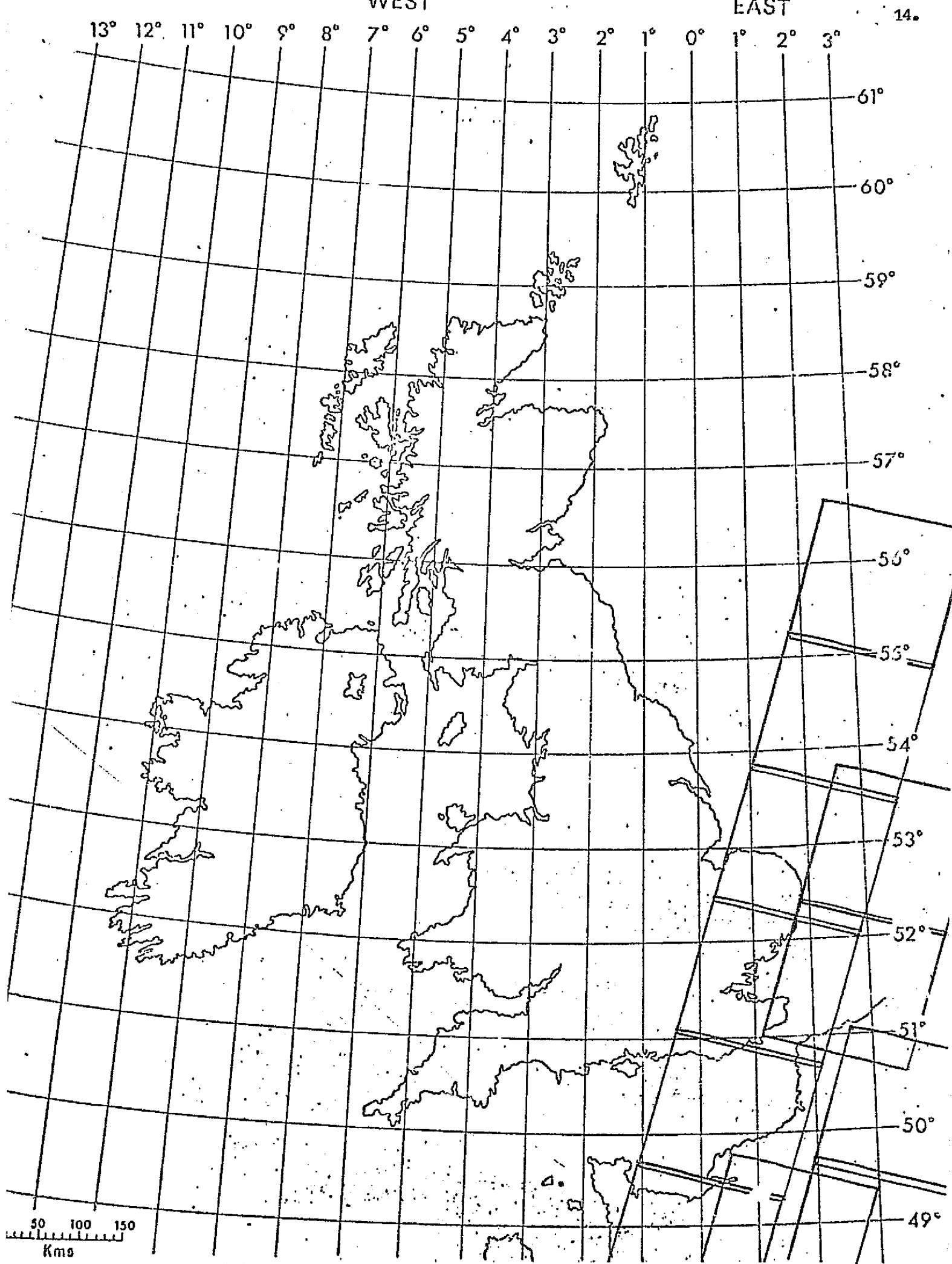


Fig. 1(f): Landsat coverage of the British Isles, Cycle 22,  
27th February - 15th March, 1976.

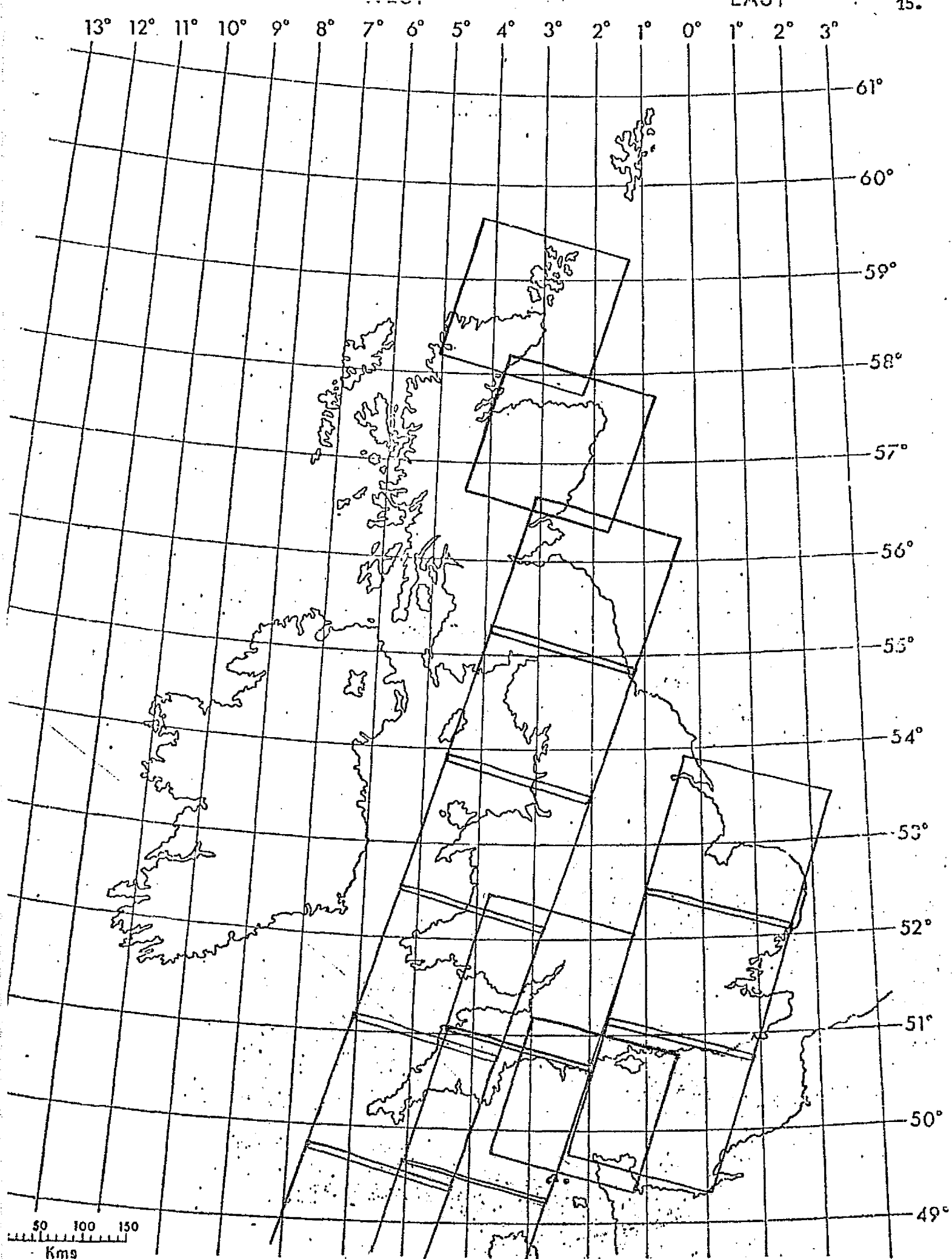


Fig. 1(g): Landsat coverage of the British Isles, Cycle 23,  
16th March - 2nd April, 1976.

Frequency

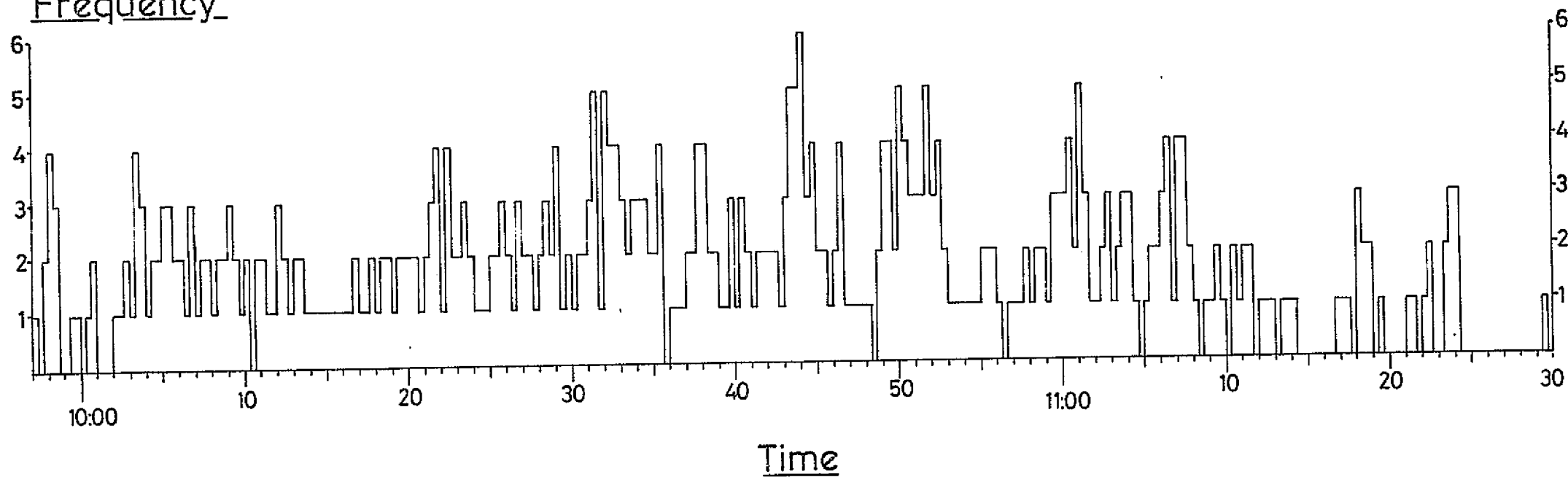


Fig. 2: Distribution of the imagery through time.

Indeed, there seems to have been a widely-accepted belief that Landsat imagery is ill-suited to cloud studies because cloudiness is thought to saturate the pictures easily (see, e.g. Danko, *ibid.* ).

Dependent as we have been on image data, not CCTs, we are not in a position to comment conclusively on this belief: there are more uncertainties in the analysis of Landsat images than CCTs, stemming mostly from picture processing. Taking as many of these uncertainties into account as we are readily able to do, and working at something less than the nominal full resolution of the Landsat images, it appears that the principal families of clouds do possess distinctive spectral signatures, and yield different histograms of picture brightness over mesoscale areas of cloud fields.

The implications of these findings are discussed in relation to other work in this Department concerned with automatic (objective) analyses of cloud imagery from meteorological satellites. The biggest potential advantage that an automatic multispectral cloud mapping methodology might enjoy over one based on single waveband data seems to be that that might be able to utilise the full spatial resolution of the original observations, rather than the reduced resolution which results from most methods of texture analysis.

The choice of sampling area was important in view of the characteristics of the cloud fields we wished to investigate, the imagery we chose to use in our analyses, and the capabilities of the equipment available for the task:

- a) Cloud field characteristics. Although it could have been possible to select a brightness threshold to represent the edge of the cloud portrayed in any image so that non-cloud areas might have been excluded from the study, we did not think it necessary or indeed desirable to take such a step. We did not want to make initial assumptions which might influence the

shapes of image brightness/frequency distributions, especially since the characteristics of cloud margins, and the spaces between adjacent structural elements of cloud fields might significantly assist in some aspects of the automatic recognition of different families of clouds.

- b) The form of the imagery. In view of the added problems that would have been associated with copying and enlarging the 70 mm transparencies provided by NASA, we decided to analyse these images themselves. At this scale 1 mm represents approximately 3.37 km on the ground.
- c) The microdensitometer. The instrument we used was a System P-1000 Photoscan, manufactured by Optronics International Inc. This is a high-speed digital microdensitometer. The machine incorporates an electro-optical rotating drum which converts photometric data on film negatives or positives to digital form for computer processing. In order that an image may be scanned it is placed over an opening in the drum, and clamped to it so that the film adheres exactly to its machined cylindrical surface dimensions.

In the present study a sampling area of  $10 \text{ mm}^2$  was chosen. We wished to sample a sufficiently large area to establish whether the brightness characteristics of fields of different categories of cloud are indeed as clear as eyeball investigations seem to suggest. It seemed likely that cloud fields should be distinguishable from one another if viewed sufficiently broadly to account for their textural characteristics; whether cloud families could be differentiated on the basis of their reflectance characteristics per unit area seemed to be more doubtful. Our hope was that, by compiling sufficiently large populations of summary statistics for quite large areas, both issues might be elucidated simultaneously, the first through areal brightness/frequency distributions, the second through the spectral reflectance graphs constructed for each

cloud category from the results for the modal classes in each brightness/frequency histogram.

Accurate registration was attempted for each set of imagery using a clean perspex mask on which were placed the locations of the four registration marks of each frame. In this way the four images of each cloud scene could be registered and a common sampling area identified.

## II TECHNIQUES

### 1. Selection of imagery

It was established earlier in this project that major cloud types can be differentiated and identified with confidence in Landsat imagery. The cloud families recognised thus were cumulonimbiform, cumuliform, stratiform, stratocumuliform and cirriform. Certain Landsat images were selected to represent "classic" forms of these cloud families and their chief members or cloud types. (See Barrett and Grant, 1976(a), especially Plates 1-5). For our multispectral study we chose one example of each cloud family, plus an example of the cumulocongestus cloud type, the latter on the grounds that cumulus humilis or mediocris and cumulocongestus have substantially different appearances in the Landsat images. Since all four spectral bands were to be investigated, there was a set of 24 cloud images to be analysed.

All 24 images depicted sea areas around the British Isles. Background brightness constitutes a serious problem for any programme of automatic analysis of cloud imagery. Methods have been devised to solve this problem (see, e.g. Miller, 1971), but none have been (or could be?) entirely satisfactory. We wished to reduce, rather than solve, the problem by analysing clouds viewed over surfaces with relatively even and constant brightness responses. Sea surfaces meet these conditions much better than land surfaces, especially in the British region, where convergences of major currents do not occur.

## 2. Selection of sampling area

This was defined on the mask by straight-edged, machine-cut, metal foil strips which overlapped to provide a precisely measured imaging area. In operation each image was orientated correctly on the mask provided for its cloud category, and the image with its mask were then located on the imaging drum.

The Koehler illumination system of the Photoscan ensures uniform illumination and focussing on the film surface via turret mounted apertures. The light transmitted through each image is measured using a photo-detector, and converted to 256 grey-levels.

The choice of scanning aperture is important, as this determines the sampling size for the imagery. The aperture sizes available for imaging on the Bristol University machine are threefold, namely 25, 50 or 100  $\mu\text{m}$  square. In the NASA Landsat Data Users Handbook (1971) (see H 1.4, 'Photographic Micro-Image Quality') the following is found:

"Because of MTF, granularity, and sensor and recording systems considerations, scans using apertures smaller than  $\approx 20 \mu\text{m}$  diameter will be essentially meaningless. Even scans with aperture sizes of  $\approx 40 \mu\text{m}$  will probably not correlate well with macro-density readings even when assuming that the investigator has made necessary corrections from specular to diffuse density"

With such considerations in mind, the largest imaging aperture size available (100  $\mu\text{m}$ ) was selected in order to minimise the sources of error. An aperture of 100  $\mu\text{m}$  square corresponds on the image to an area of approximately 337 metres square on the ground. Thus approximately 16 pixels were analysed in each of our microdensitometer spot readings.

## 3. Operating practices

The illuminating and imaging optics of the Photoscan are mounted on opposite sides of a "C" carriage through which the cylinder drum rotates.



The optical density of each image is measured every 100  $\mu\text{m}$  along the circumference of the drum (Y direction) within the pre-determined area. After each revolution the "C" carriage is stepped in the axial (X) direction by 100  $\mu\text{m}$ . In practice these processes were repeated until the whole 10  $\text{mm}^2$  area of each image had been scanned. Once per revolution, through an opening in the drum opposite the film position, the densitometer photo-detector system is reset to a given known value which represents an optical density of zero as defined by the air path through the slot. Since the drum speed is high (8 revs. per second) the drift of the instrument is far less significant than the least significant bit of density data.

The detector voltage resulting from light transmitted through each image is amplified logarithmically, digitized, displayed, and recorded by interfacing the scanner with a magnetic tape recorder. Each number is representative of a grey-level in the selected density range. In our case the density range was 0 to 2D. Within this range density bears a linear relationship with the output grey levels.

Optical density (D) is defined as:

$$D = \log \frac{I_i}{I_t}$$

where

$I_i$  is the light intensity impinging on the detector through an air path and

$I_t$  is the light intensity of the transmitted light.

In addition to the 10  $\text{mm}^2$  sampling area on each image, the 15 step grey-scale tablet was scanned. This scale has undergone the same copying and processing as the image to which it is attached (NASA, 1971, pages 3-5).

#### 4. Data output

Output from the microdensitometer was recorded on a magnetic tape unit for subsequent processing on a PDP 11/45 mini-computer.

Initial processing was concerned with the recording brightness values of the 15-step grey-scale tablet of each image. A number of data records were examined for each image and the upper boundary value of each of the 15 steps was determined by inspection of the computer print-out. Preferably some type of edge-detection logic (e.g. Rosenfeld, 1970) should have been employed, but this time did not permit. Once the upper boundaries of each step had been determined these values were fed back into the computer in order that the frequency distribution of brightness values for each image could be determined. This procedure was adopted so that we might be able to relate different frequency classes to actual tones on each Landsat image, rather than some arbitrarily chosen density value which might be inappropriate in view of the apparent variations in image processing.

Besides the frequency distributions of the brightness values, other summary statistics were computed also, including means, standard deviations, skewness and kurtosis.

The mean brightness value for each image was determined in the following manner. The store size of the computer is limited (24 k) and was not large enough to hold all the values of each image (8000-9000). Thus the mean brightness value of each record (Y-axis scan) was calculated and the final mean was taken as the mean of the record means. The Standard Deviation was calculated using the final mean derived as outline above. Skewness and kurtosis values were not found directly on the PDP 11/45 because of problems with the computer program. These were calculated from the frequency distributions using a Hewlett Packard 9801A calculator and an appropriate library program (Prog. 1-3).

### III RESULTS

#### 1. Brightness characteristics of Landsat positive transparencies

For analytical purposes, all the brightness values produced by the microdensitometer in terms of 256 grey-levels were converted to optical density values in the range 0 to 2D. This was a straight-forward procedure as the density bears a linear relationship with the grey-levels, as noted previously.

Fig. 3 shows the 15-step grey-scale tablets, plotted as a function of density and waveband. The divisions correspond to the upper limit of each step, the procedure for determining which was outlined above. Step 8 of each wedge is shaded to act as a reference. Step 1 (white) is at the left-hand side, and step 15 (black) is at the right-hand side.

Perhaps the most important fact emerging from this diagram is the wide variation of step width. Generally, the brighter steps, with densities less than 1D, are narrower than the darker steps with densities greater than 1D. The first step is somewhat anomalous in that it has no lower limit. Another notable feature is the variation from image to image in position of similar steps. This variation occurs both between wavebands for a particular frame, and also between one frame and another. Thus, for example, in the illustration of cumulus humilis, corresponding steps of band 7 are generally brighter than those of band 6. Such differences are due in part to variations in the processing of Landsat images.

A serious problem of interpretation therefore arises. Are the differences in brightness in a particular scene in different wavebands due principally to differences in target reflectance, or differences in processing? It is clear from our results that the influences of image processing must be borne in mind constantly as we move towards drawing conclusions from these data. Ideally, the two components of variation should be determined and separated; this we could not achieve in our study.

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Density

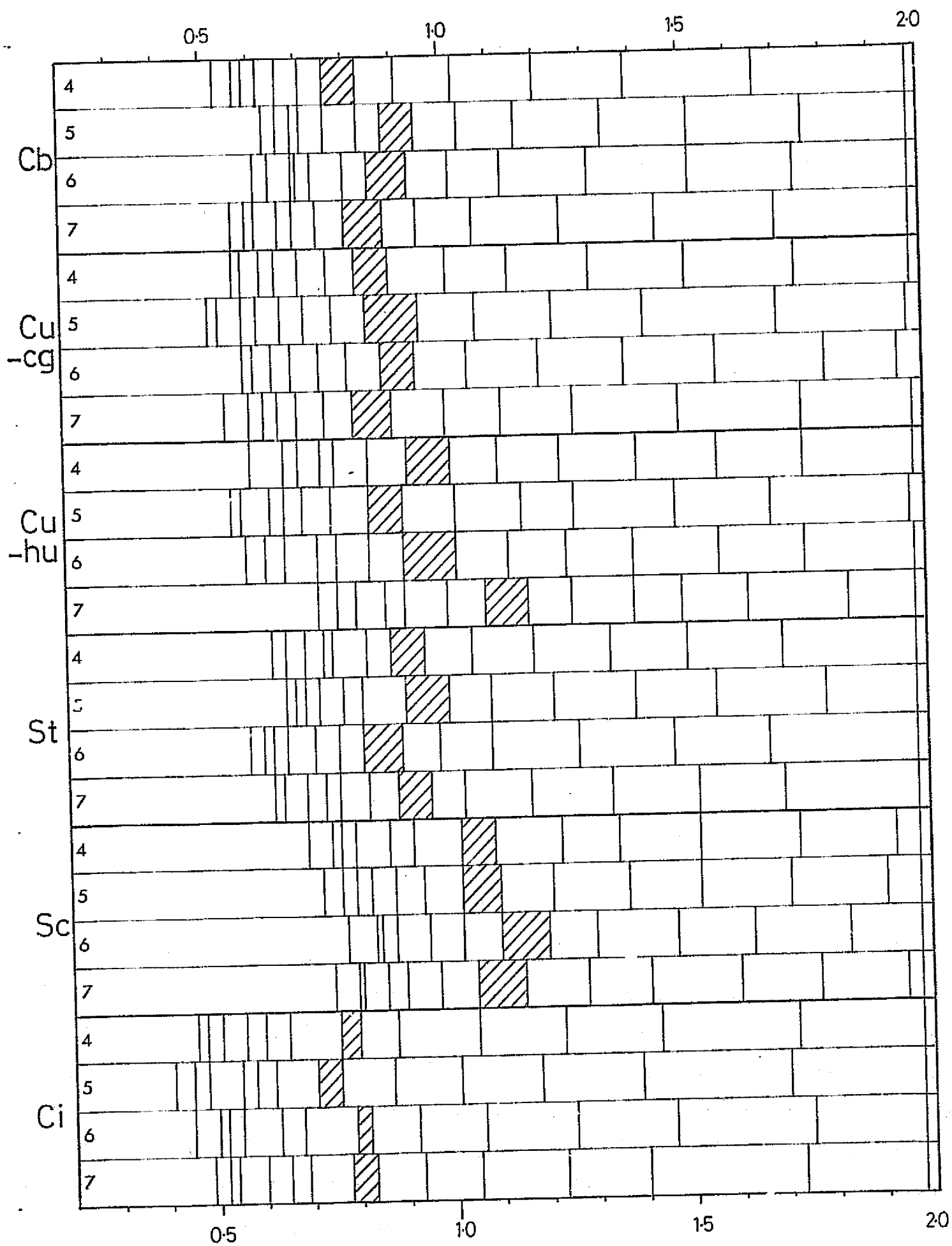
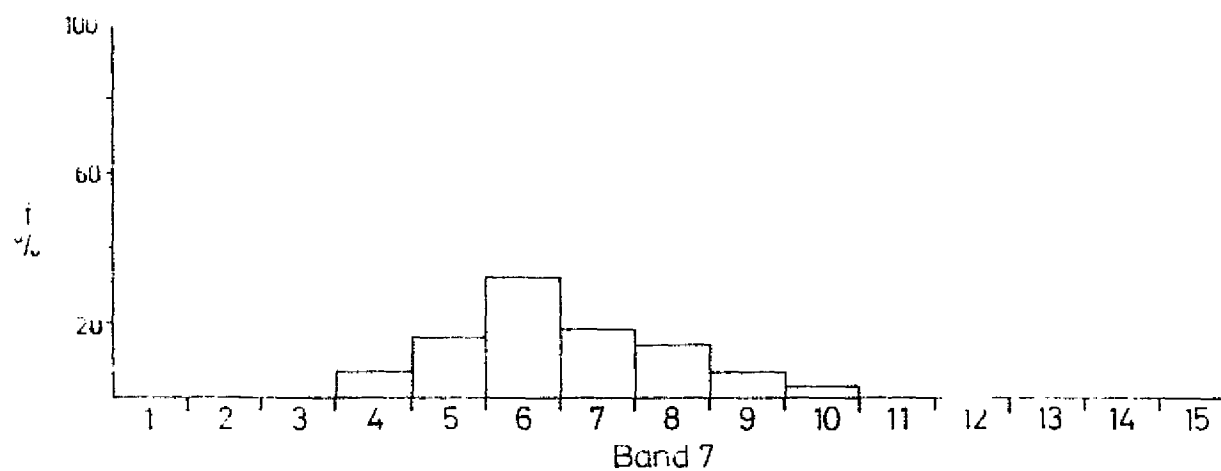
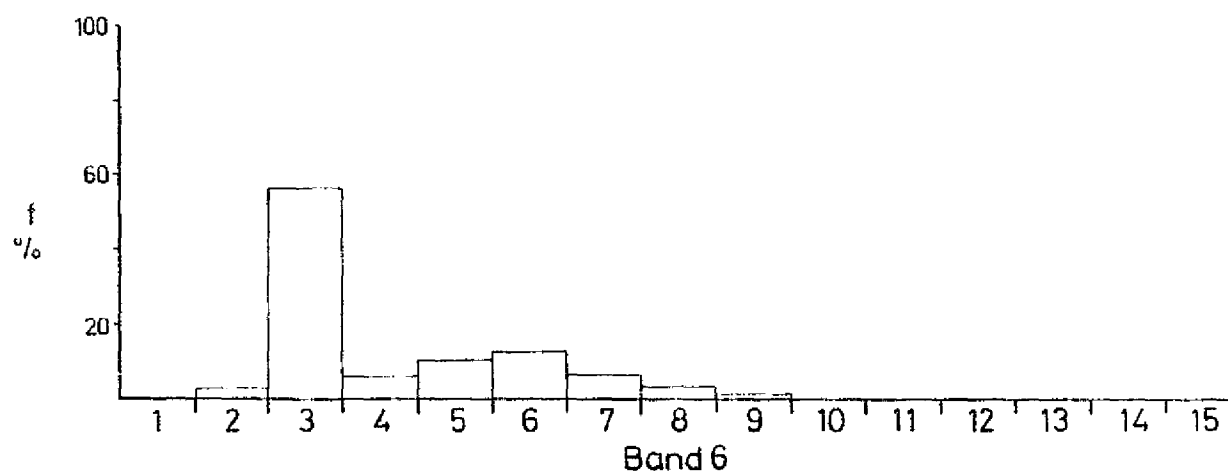
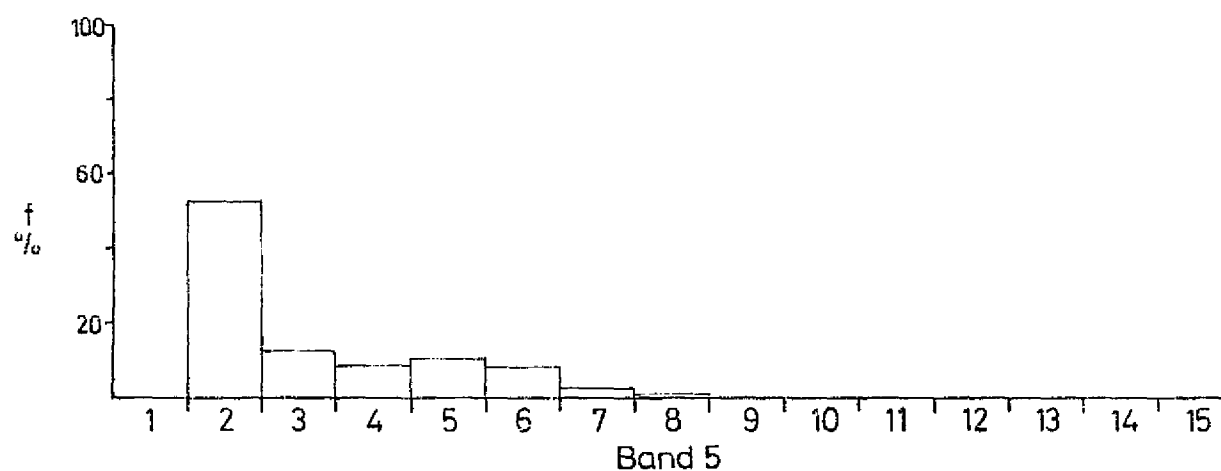
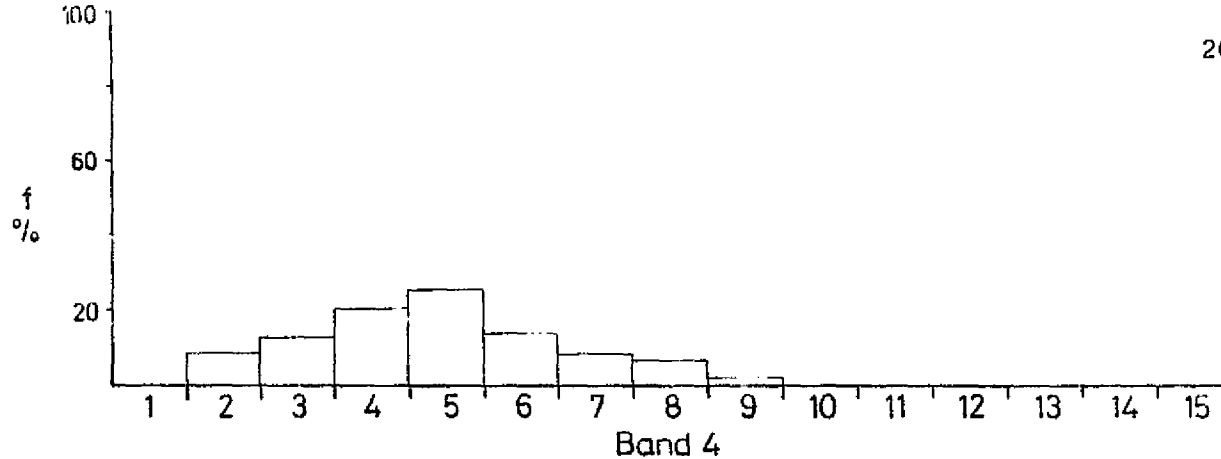


Fig. 3: Grey-Scale Tablets.

## 2. Brightness characteristics of six categories of clouds: graphical results

Figs. 4 a to f show frequency distributions of individual cloud types in each waveband in relation to the 15 step grey-scale. Frequencies have been converted from number counts to percentages to facilitate comparison between different cloud types. Notwithstanding our earlier comments on variations in picture processing, some important differences do occur.

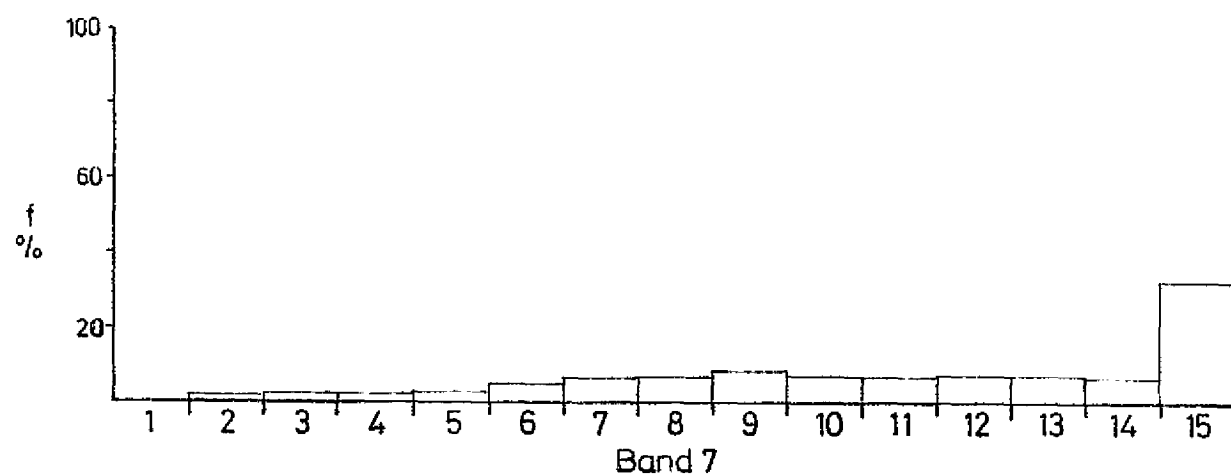
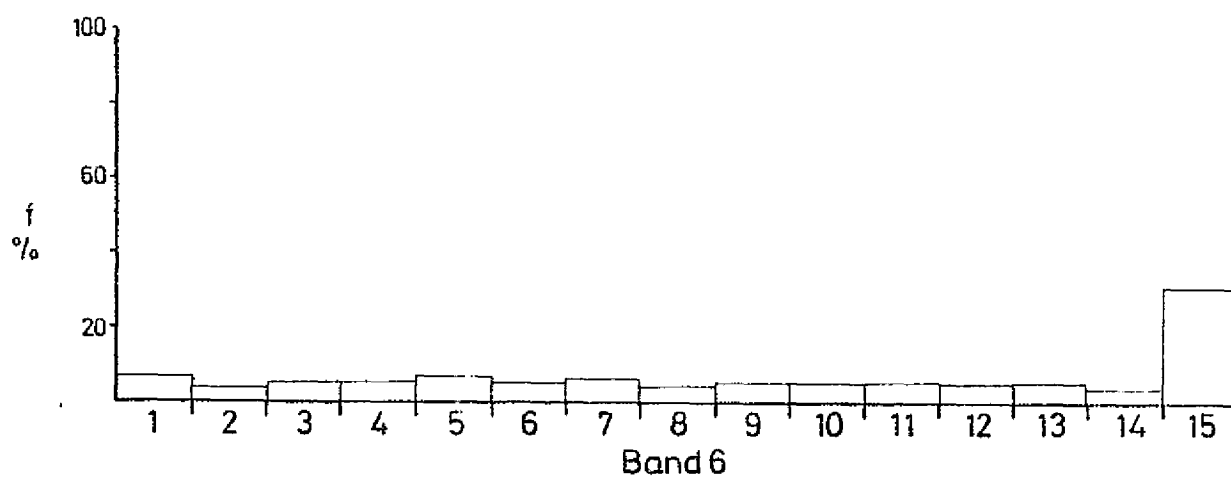
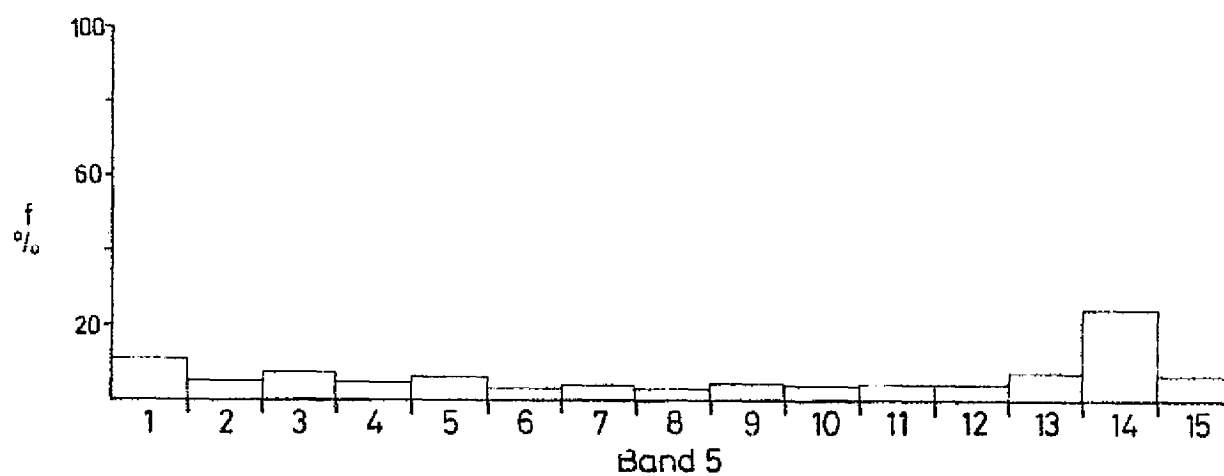
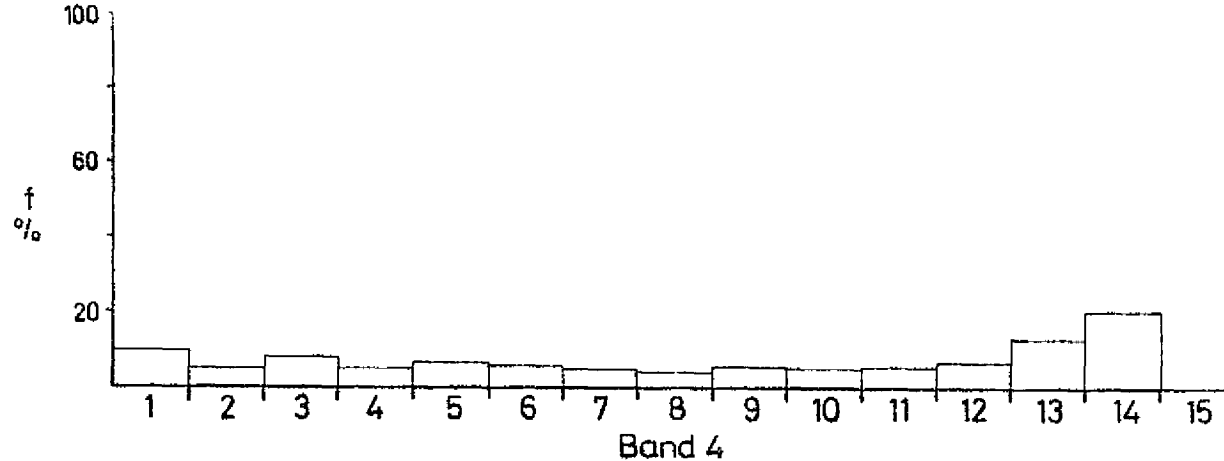
- a) Cumulonimbiform (Fig. 4(a)): Bands 4 and 7 show apparently similar distributions, with band 7 being displaced slightly towards the darker end of the scale. Bands 5 and 6, however, possess a strong modal category, well displaced towards the brighter end of the scale.
- b) Cumulus congestus (Fig. 4(b)): The frequency distributions of all four wavebands range across the whole step-wedge scale. All the distributions are essentially similar, some minor differences, occurring at the dark end of the scale in steps 14 and 15.
- c) Cumulus humilis (Fig. 4 (c)): Unlike the cumulus congestus graphs of Fig. 4(b), these distributions are restricted in range to the darker end of the scale. This reflects the lower brightness responses of these small cloud cells and the larger areas of dark sea background between them.
- d) Stratiform (Fig. 4(d)): Each waveband shows a marked clustering of values at the bright end of the scale, indeed in band 5 almost 100% of the data points are contained within the brightest step. This is undoubtedly due to extensive saturation of the image by this cloud type. The distributions of bands 6 and 7 show tails extending well into the darker portion of the scale.
- e) Stratocumuliform (Fig. 4(e)): Bands 4 and 5 have similar distributions, extending across a wide range of values, peaking



NB. Values <1% not shown

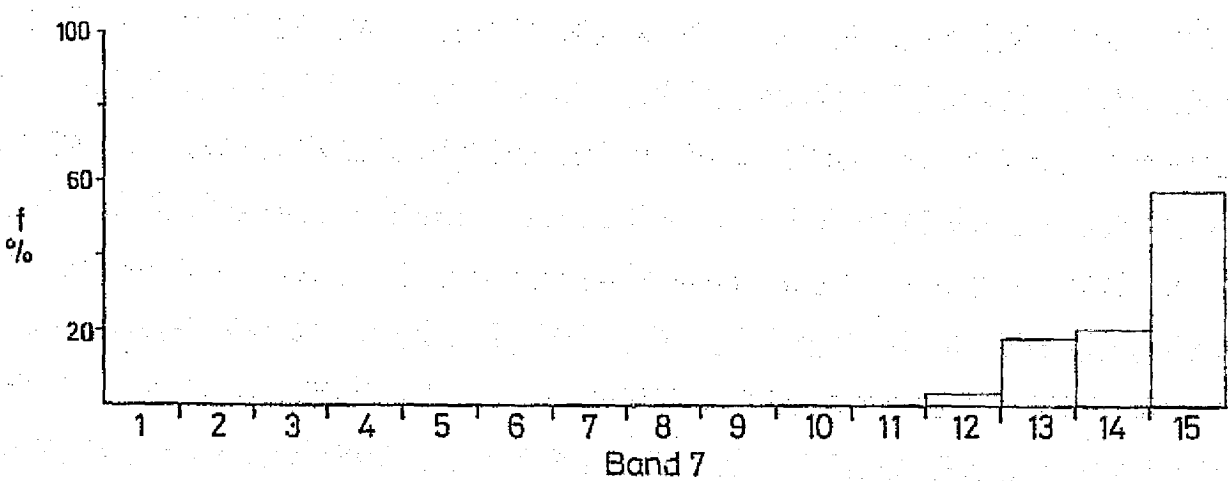
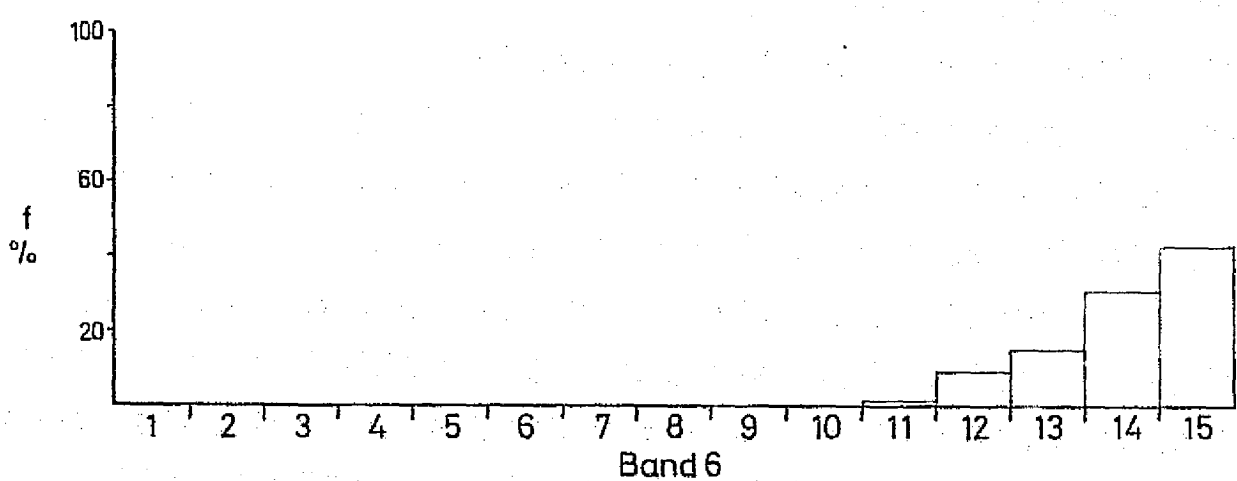
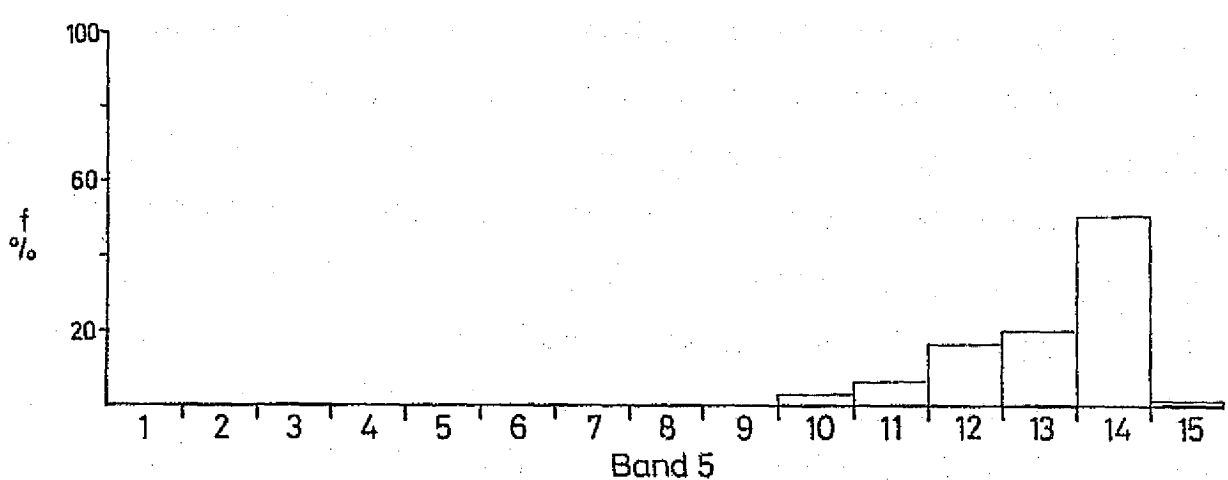
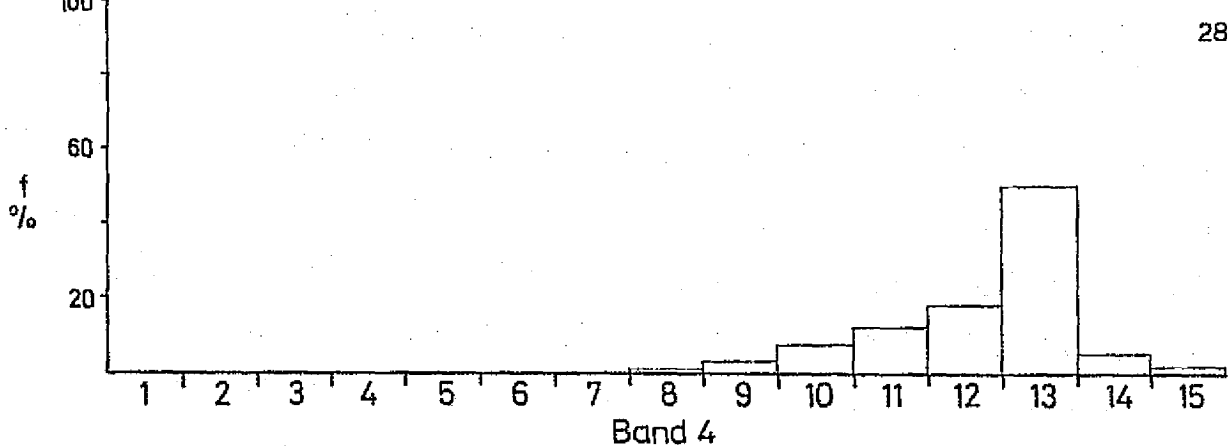
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Fig. 4(a): Cumulonimbiform: Frequency Distribution.



N.B. Values  $<1\%$  not shown

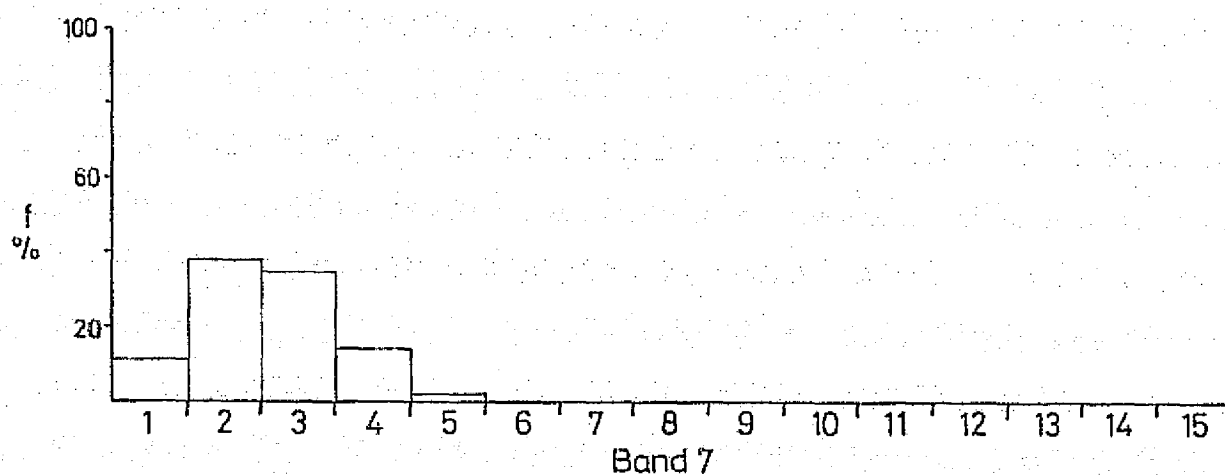
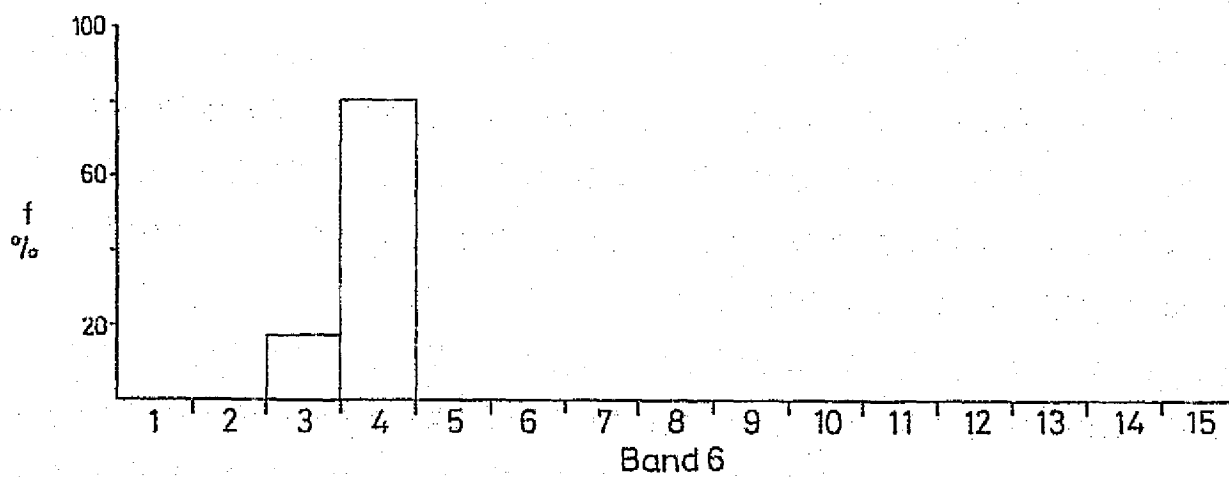
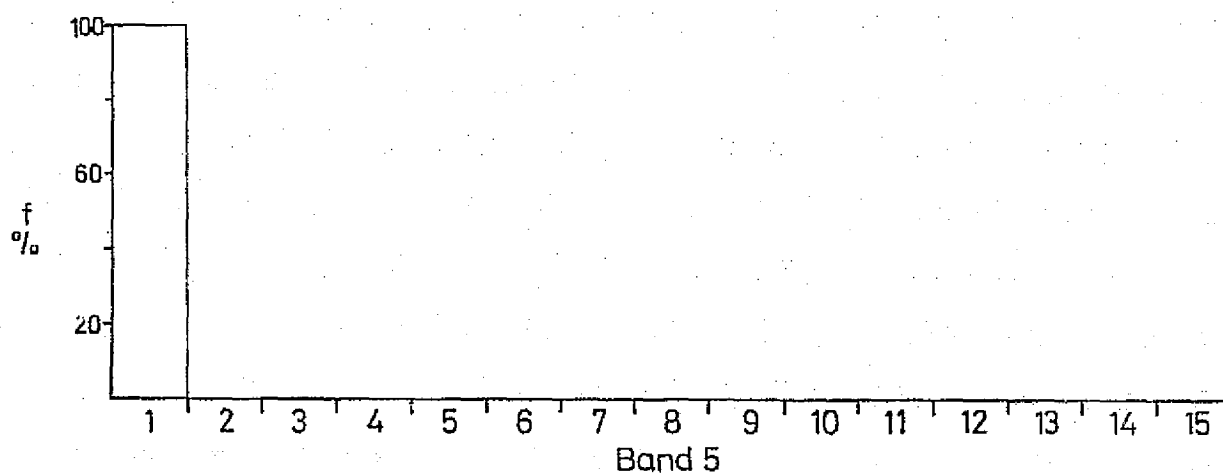
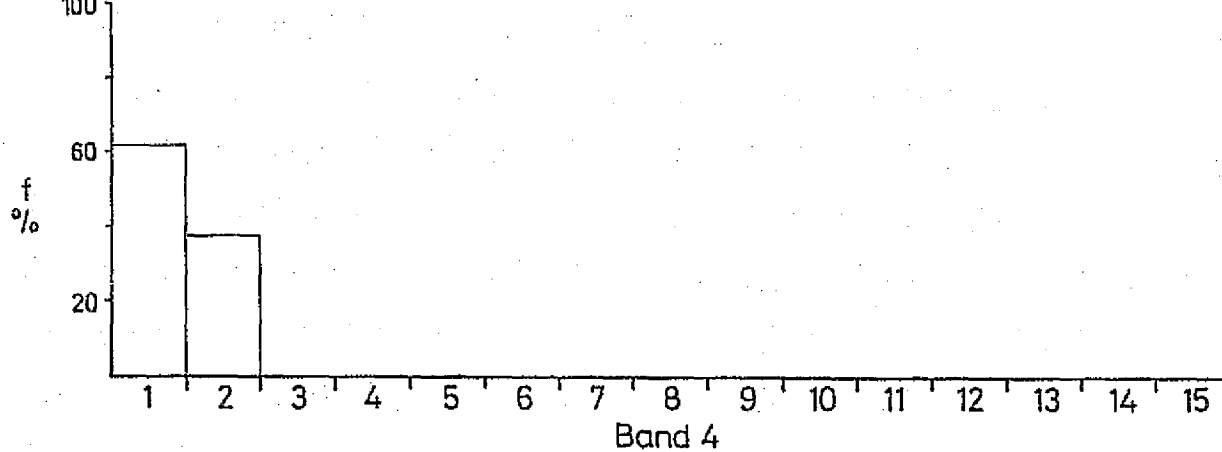
Fig. 4(b): Cumulus congestus: Frequency Distribution.



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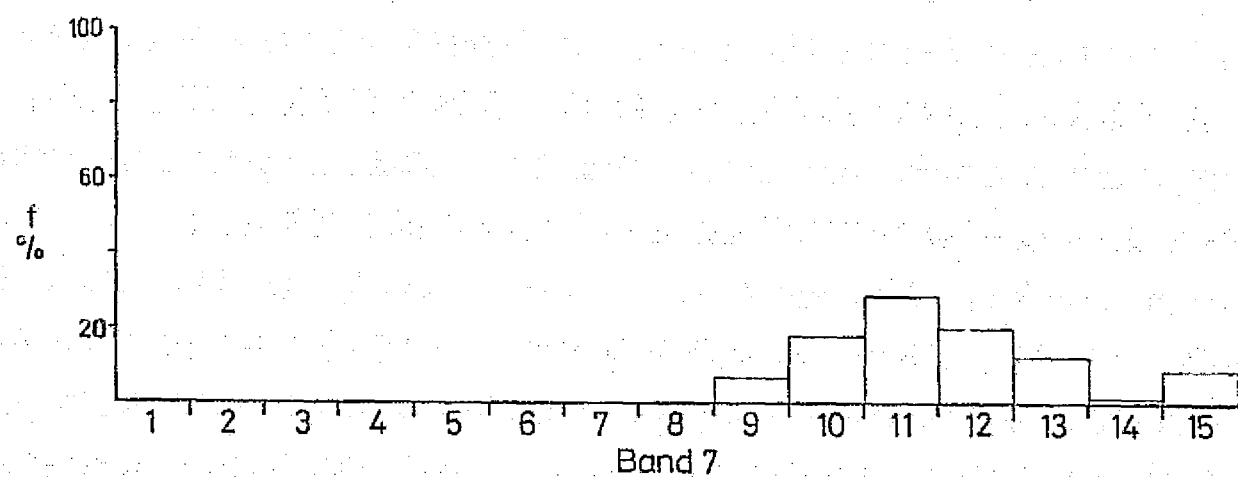
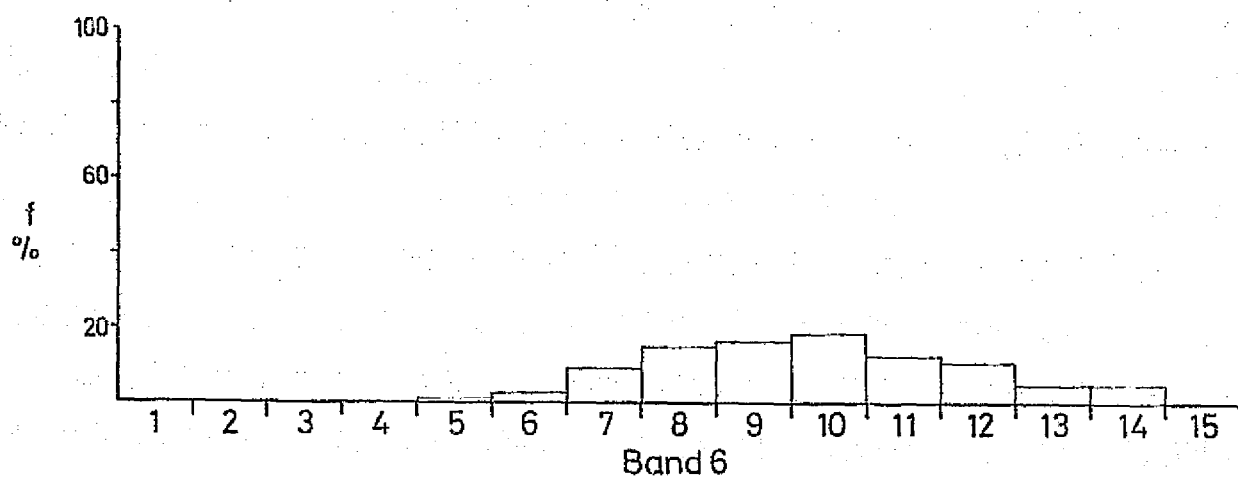
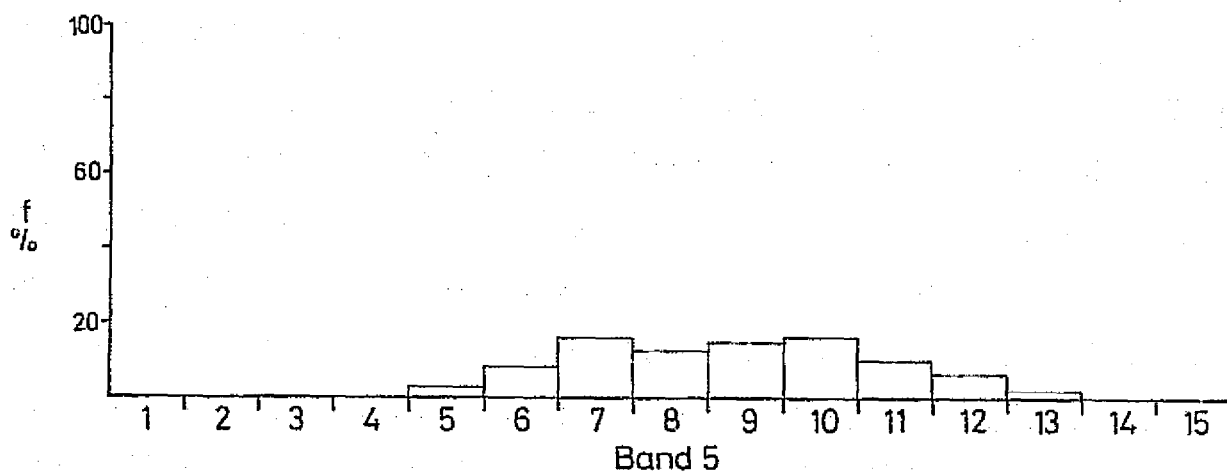
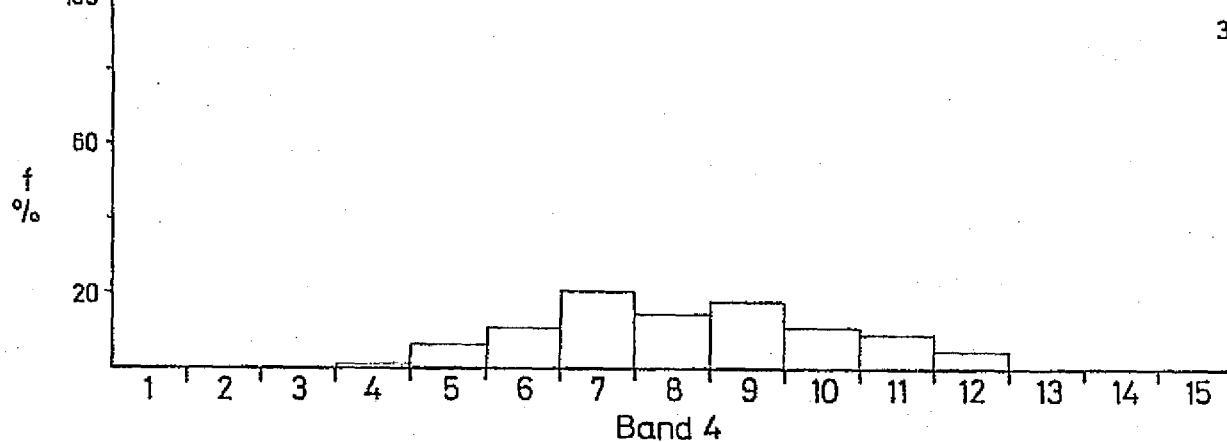
Fig. 4(c): Cumulus humilis: Frequency Distribution.





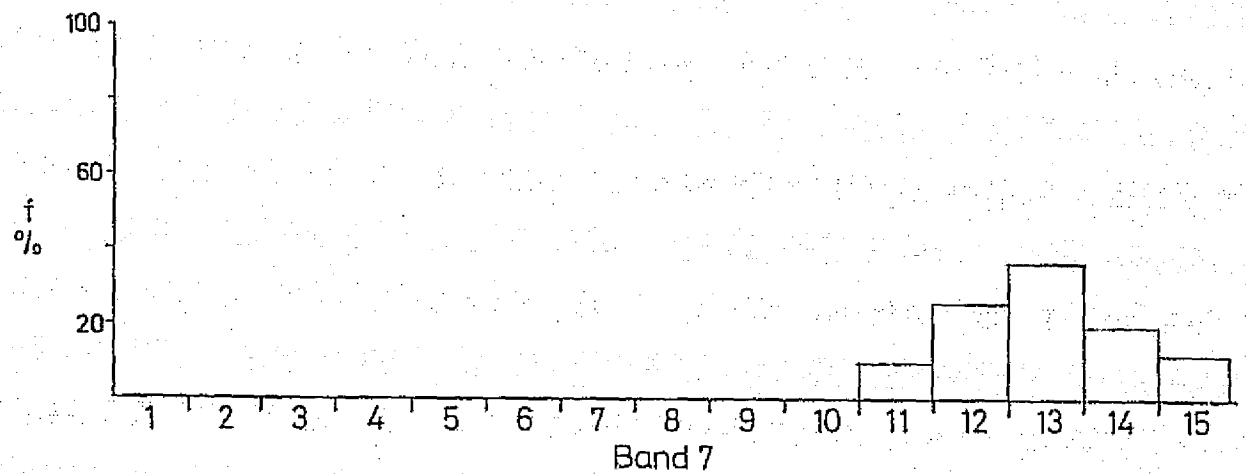
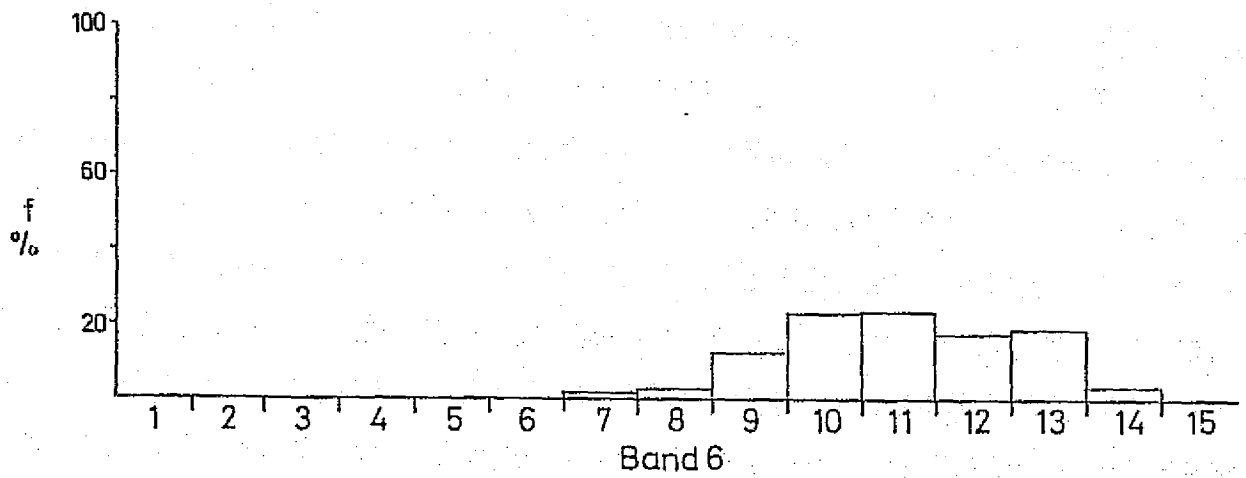
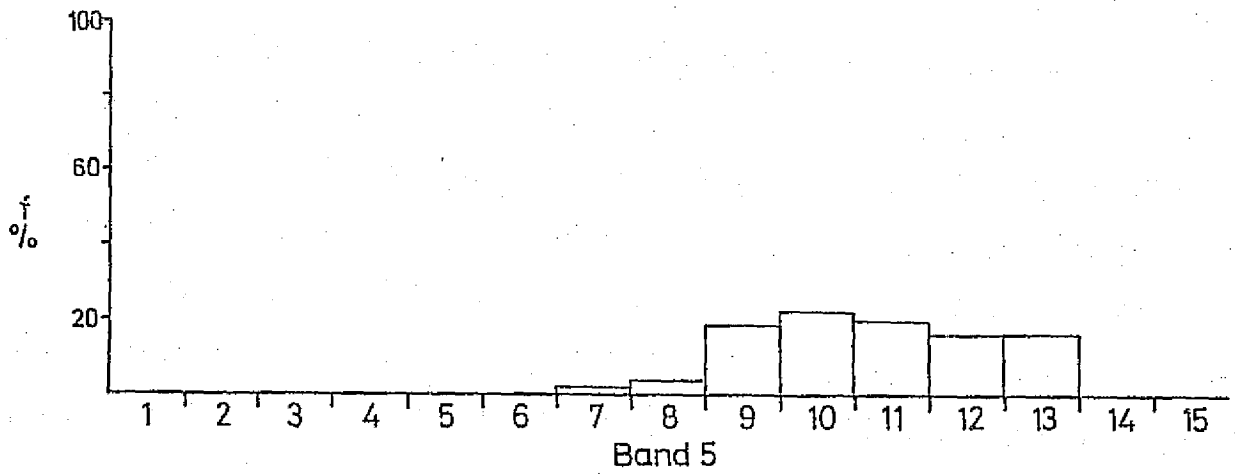
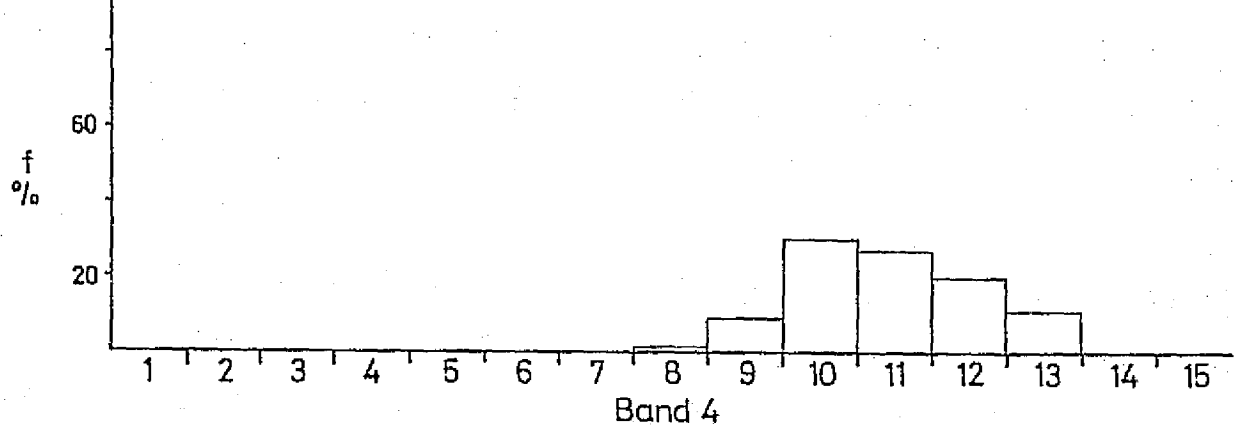
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Fig. 4(d): Stratiform: Frequency Distribution.



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Fig. 4(e): Stratocumuliform: Frequency Distribution.



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Fig. 4(f): Cirriform: Frequency Distribution.

gently in the centre of the scale. In band 6 there is a slight displacement towards the dark end of the scale. In band 7 there is a significant displacement towards the darker end of the scale, and the range of values is more restricted.

- f) Cirriform (Fig. 4(f)): Bands 4, 5 and 6 are similar to one another, with distributions located in the darker portion of the scale and a fairly wide range of values (over 8/9 steps). Band 7 possesses a marked displacement towards the dark end of the scale and the range of values is limited to the darkest 6 steps.

Figs. 4(a)-(f) reveal, therefore, that differences in brightness occur both between the wavebands for individual cloud types as well as, more strikingly, between similar wavebands for different cloud types. To facilitate the examination of these differences, cumulative frequency distributions were plotted. (See Figs. 5(a)-(d)).

These graphs consist of plots of percentage cumulative frequency on an arithmetic probability scale, against image density on an arithmetic scale. First, the average density of each step was found. In the case of step 1 the average density was found by determining the average density range of steps 2 to 5 inclusive. This value was then halved, and subtracted from the upper limit value of step 1 to provide an average value for the brightness of that step. The advantage of using arithmetic probability paper in this analysis is that if the distributions plotted are normal, then a straight line will occur on the graph. A brief examination of these diagrams shows that the distributions were not normal. The chief points that emerged from this analysis were as follows:

- a) Band 4 cumulative frequency distributions (Fig. 5(a)). Here stratiform and cumulonimbiform clouds appear to give similar results, both having the majority of their values at the bright end of the scale. Similarly cirriform and stratocumuliform clouds are similar to each other, their curves lying close together

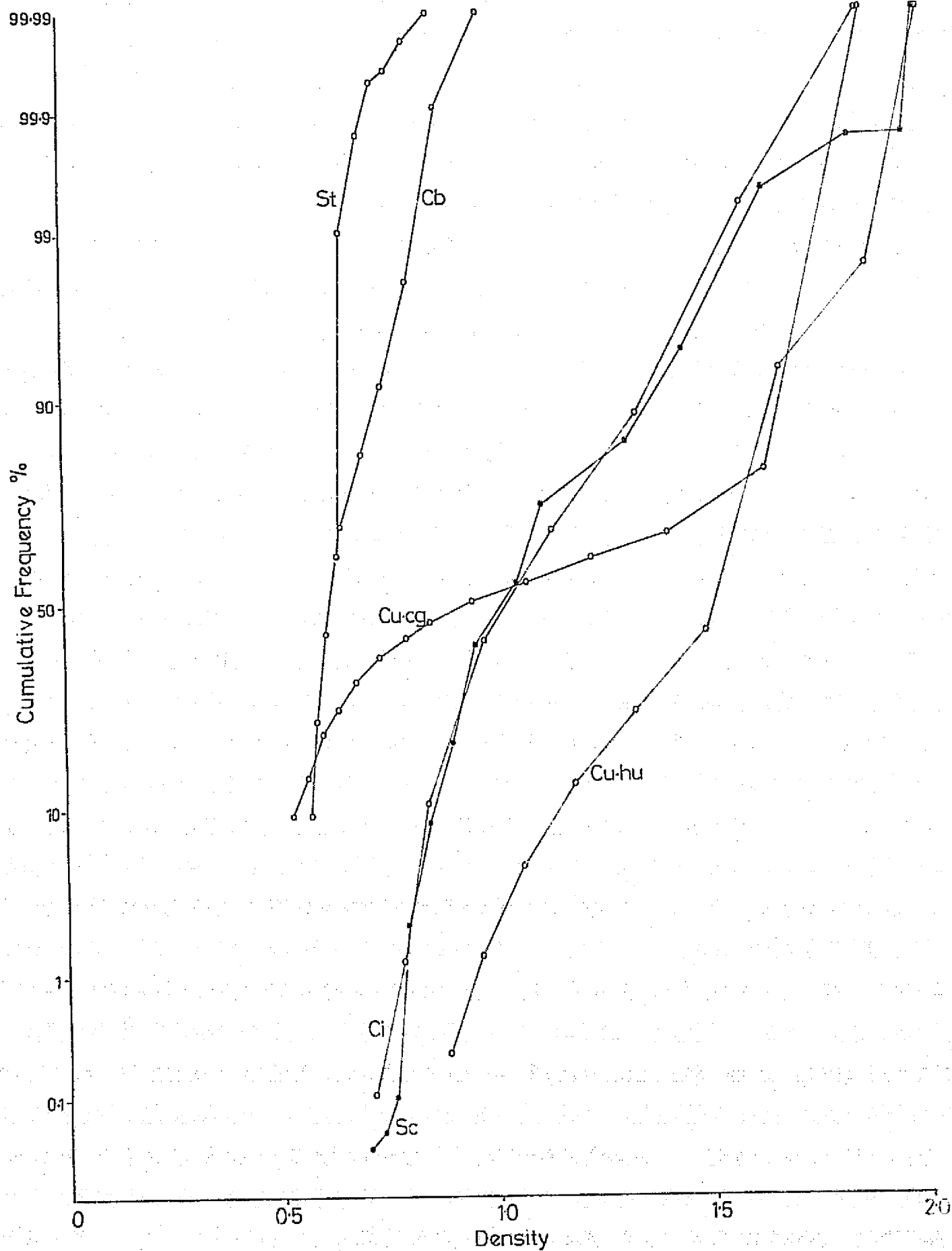


Fig. 5(a): Band 4 Cumulative Frequency Distributions.

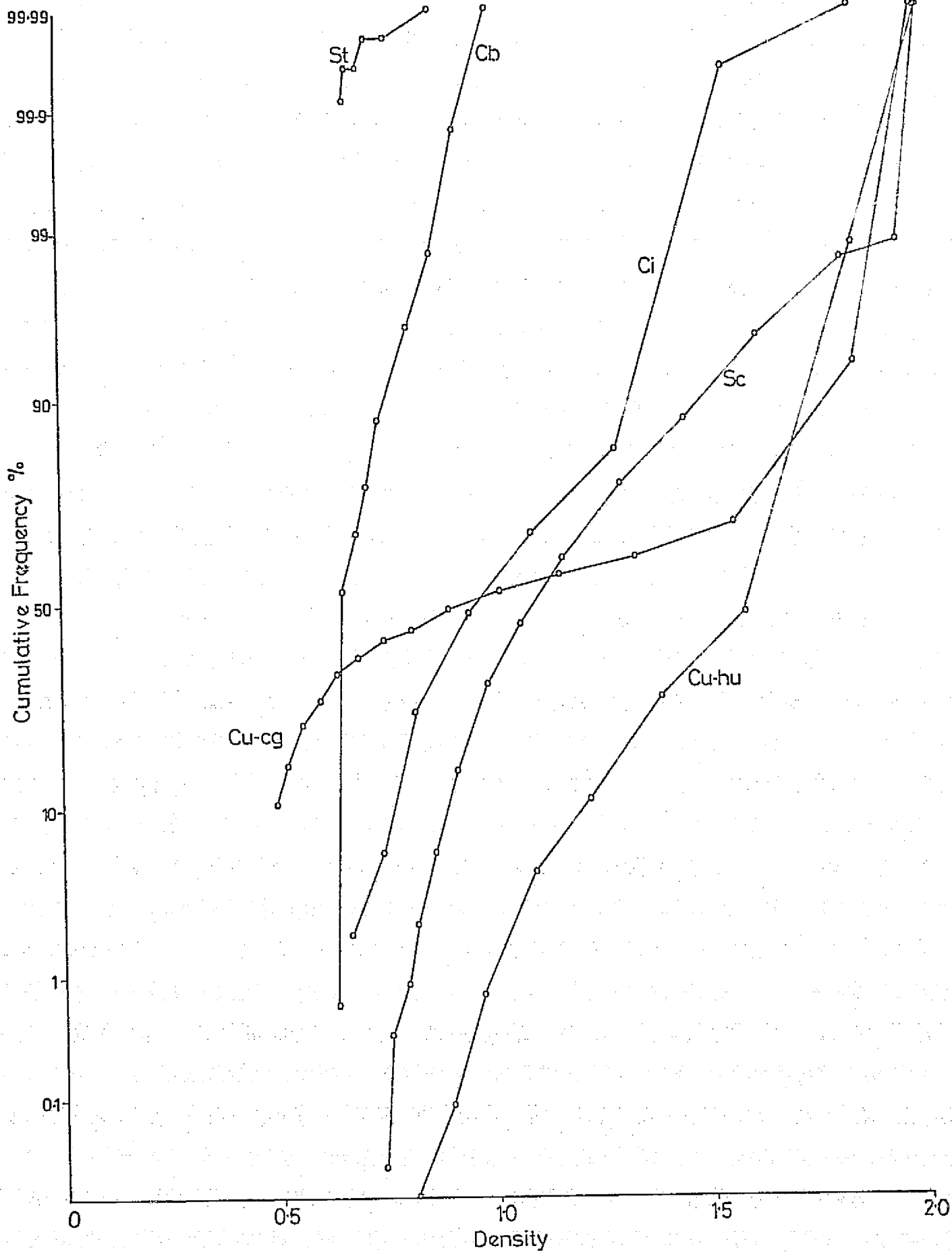


Fig. 5(b): Band 5 Cumulative Frequency Distributions.

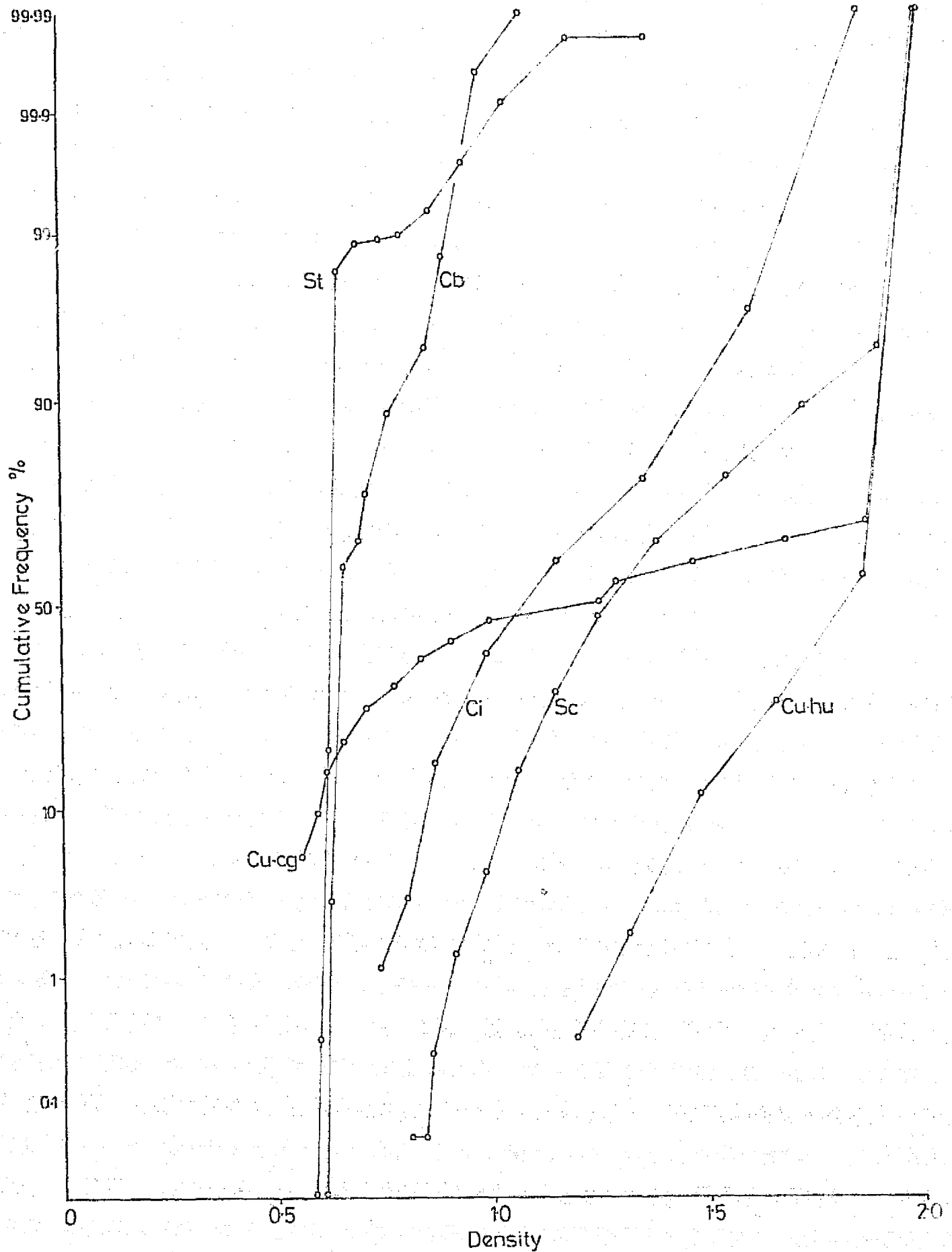


Fig. 5(c): Band 6 Cumulative Frequency Distributions.

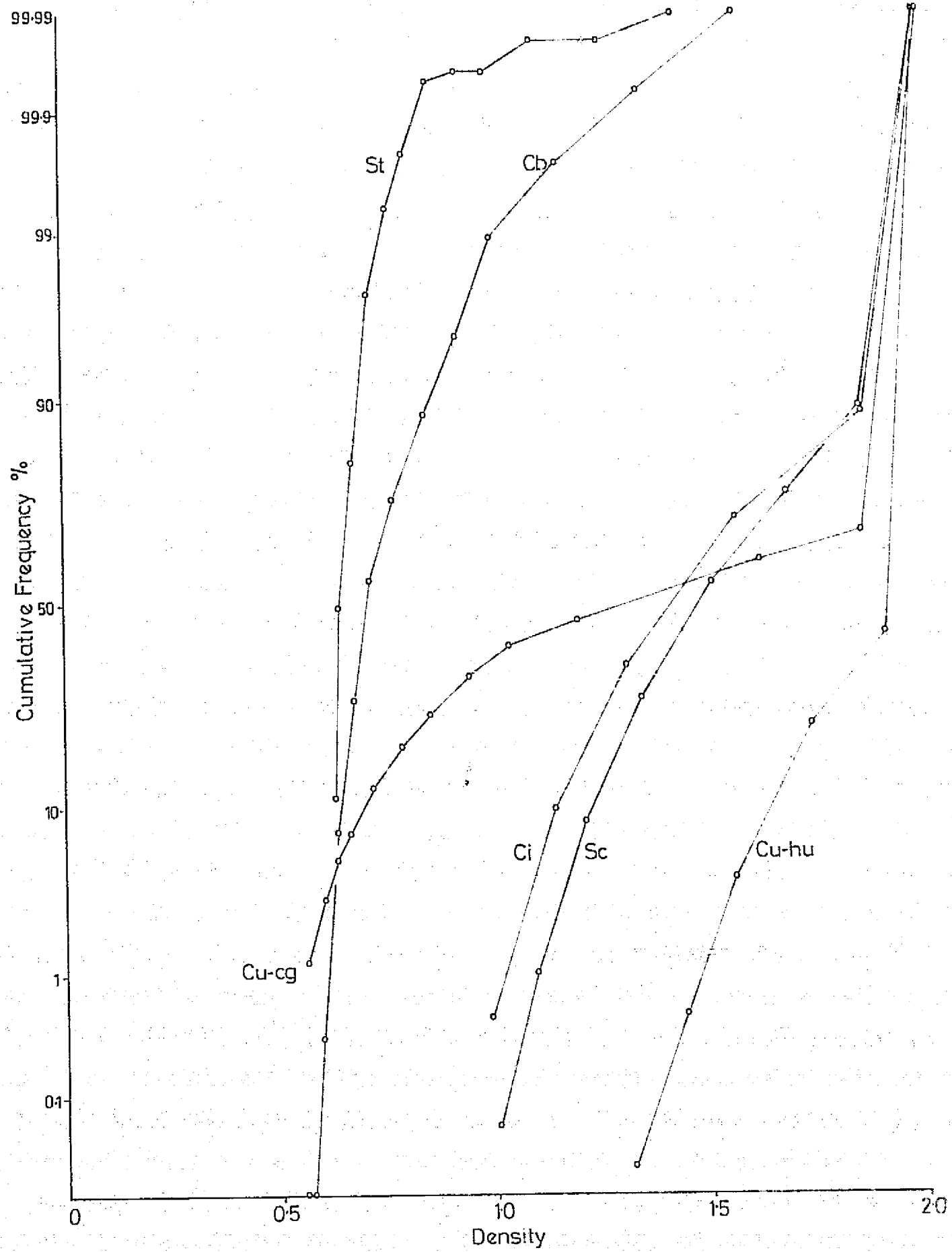


Fig. 5(d): Band 7 Cumulative Frequency Distributions



across much of the graph. At first sight this may appear strange as the graphs of their respective frequency distributions (Figs. 4(e) and 4(f)) apparently revealed considerable differences. However, when one examines Fig. 3, it can be seen that stratocumuliform grey-scale values are considerably brighter than corresponding cirriform values. This is taken into account more fully in Fig. 5(a) where actual density values are employed on the abscissa, not grey-scale step numbers as in Fig. 4.

Generally, most cloud types follow paths which are roughly parallel over much of the scale in Fig. 5. The most notable exception to this is cumulocongestus. The plot for this cloud category starts well to the left of the graph and generally rises less steeply than those for the other cloud types except at the dark end of the scale. The tendency for this cloud type then, is for its plot to cut across the plots for cirriform, stratocumuliform and cumulus humilis.

- b) Band 5 cumulative frequency distributions (Fig. 5(b)): These are essentially similar to the band 4 plots in Fig. 5(a). However, the stratiform curve is shorter due to the clustering of its values at the bright end of the scale. The cumulus congestus curve again lies across those for the other types.
- c) Band 6 cumulative frequency distributions (Fig. 5 (c)): For the first time stratiform extends into darker portions of the scale than does cumulonimbiform. Stratocumuliform is now markedly displaced towards the dark end of the scale in comparison to cirrus. Cumulus humilis is similarly displaced towards darker levels, although it retains its approximately parallel position with respect to cirriform and stratocumuliform. Cumulocongestus intersects the other distributions at quite large angles, as in bands 4 and 5. At the dark end of the scale,

the final 30% of its distribution follows a similar path to that of cumulus humilis.

- d) Band 7 cumulative frequency distributions (Fig. 5(d)): In this waveband, cumulonimbiform has been displaced quite markedly towards the dark portion of the scale. The whole of its curve is on the darker side of the stratiform curve. Cirriform and stratocumuliform distributions now follow very similar paths, both having been displaced markedly towards the darker portion of the scale than in band 6. Cumulus humilis is darker than in band 6. This is probably due to the darkening of the sea background which comprises a larger proportion of this image between the small cumulus cells. This effect is also seen in the case of cirriform and stratocumuliform, both of which contain some areas of sea in the imaging area.

These diagrams, Figs. 5(a)-(d), show that marked differences in reflectance characteristics do occur between cloud types and that these differences change from one waveband to another. It is thought that such differences are indeed due principally to target characteristics, not processing practices, for more account is taken of the grey-scale differences in these diagrams through the use of the actual density values of the steps rather than their numbers in the grey-scale.

### 3. Brightness characteristics of six categories of clouds. summary statistical results

In addition to such graphical descriptions of the brightness frequency distributions, it is possible to gain further insight into the nature of cloud differences by deriving summary statistics via the method of moments. This is a computational method; the analysis of the mean and standard deviation was carried out on the PDP 11/45 mini-computer. Skewness and kurtosis coefficients were determined on a Hewlett-Packard calculator

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from the frequency distributions derived by the PDP 11/45. The results of the computations are presented in Table 2.

There are some interesting differences between the summary statistics and the impressions gained of the distributions presented in Figs. 4(a)-(f). For example, the cumulonimbiform statistics show that the kurtosis ("peakedness") of the distributions increases steadily from band 4 through to band 7. An examination of Fig. 4(a) alone would probably have led one to conclude that bands 5 and 6 were more "peaked" than either bands 4 or 7. Cumulocongestus clouds show relatively large standard deviations, a fact less unexpected when Fig. 4(b) is examined. A small negative skewness value is noted in band 7 which corresponds to the increased frequency of values at the dark end of the scale (step 15). The cumulus humilis distributions (Fig. 4(c)) are asymmetrical in nature and this produces negative skewness values for all wavebands. Mean brightness values show a similar trend in all the cloud types. Generally, the mean brightness of each successive waveband is slightly darker than the preceding waveband. There are two exceptions to this general rule. Both occur in waveband 5 in the cirriform and stratiform cloud types. Such a decrease in brightness with waveband is probably explained by the decreasing brightness of the background area (the sea) with successive wavebands.

Besides this slight anomaly in the general trend of mean brightness values, stratiform clouds also present some other noteworthy summary statistics. The skewness values recorded are very large, indicating extreme asymmetry of the distribution. This is perhaps not surprising when Fig. 4(d) is examined, especially with respect to band 5. However, the kurtosis values seem excessively high when one considers that in sediment analysis values of kurtosis greater than 3.00 indicate extreme leptokurticity (peakedness) and are uncommon.

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TABLE 2

<u>Cloud Type</u>	<u>Waveband Number</u>	<u>No. of Data Points</u>	<u>Mean</u>	<u>S.D.</u>	<u>Skewness</u>	<u>Kurtosis</u>
Cumulonimbiform	4	9215	0.65	0.07	1.09	4.13
	5	9215	0.69	0.06	1.75	5.94
	6	9215	0.71	0.07	1.78	6.02
	7	9215	0.76	0.10	1.90	10.05
<u>Cumulus congestus</u>	4	8084	1.13	0.49	0.27	1.46
	5	8084	1.17	0.58	0.22	1.35
	6	8084	1.23	0.57	0.09	1.31
	7	8084	1.40	0.52	-0.09	1.39
<u>Cumulus humilis</u>	4	9025	1.55	0.22	-0.70	3.07
	5	9025	1.63	0.23	-0.82	2.54
	6	9025	1.85	0.19	-1.17	3.44
	7	9025	1.92	0.12	-1.53	4.52
<u>Stratiform</u>	4	8272	0.63	0.01	1.62	13.44
	5	8272	0.57	0.01	50.95	2789.26
	6	8366	0.64	0.04	10.87	168.44
	7	8366	0.66	0.04	3.03	45.02
<u>Stratocumuliform</u>	4	9100	1.12	0.22	0.79	3.21
	5	9100	1.20	0.26	0.87	3.29
	6	9100	1.40	0.28	0.55	2.35
	7	9100	1.59	0.23	0.17	2.08
<u>Cirriiform</u>	4	7896	1.14	1.14	0.63	2.71
	5	7896	1.09	1.09	0.49	2.09
	6	7896	1.21	1.21	0.49	2.26
	7	7896	1.57	1.57	0.10	1.96

#### 4. Spectral reflectance graphs for six categories of clouds

The results summarised in sections (1) - (3) above are all related to characteristics of cloud fields viewed over areas of about  $33.7 \text{ km}^2$  on the ground. It would be interesting to investigate the degrees of similarity between those results and others for a range of smaller areas. Whilst we must be cautious not to read too much into the results obtained, it seems legitimate to attempt to interpret them in terms of what they may indicate concerning the characteristics of cloud elements viewed by the microdensitometer over areas of about  $337 \text{ m}^2$  on the ground. Taking the modal classes in Figs. 4(a)-(f) to indicate the most representative brightness values for each cloud category in each waveband we have compiled a set of spectral reflectance graphs for the six cloud examples (see Figs. 6(a)-(f)). It appears therefrom that the spectral reflectance signatures for different categories of clouds possess some marked differences both in form and position on the axes. Not surprisingly the cumuliform and cumulocongestus curves are generally similar, whilst the stratiform and cumulonimbiform curves are disappointingly alike.

It would seem well worthwhile investigating the multispectral differences of Landsat-imaged clouds more carefully, perhaps through the use of digital data from the CCTs so that the full resolution of the imagery might be employed and picture processing problems thereby eliminated.

#### 5. Discussion

It is in the field of sedimentary petrology and geology that this type of statistical analysis has reached its greatest sophistication. The technique of moment analysis has been used to identify and differentiate sediments (e.g. Folk and Ward, 1957) and in the interpretation of the depositional histories of different sediments (e.g. Greenwood, 1972). Generally, bivariate plots have been employed, with each of the four summary statistics being plotted in turn against each of the others.

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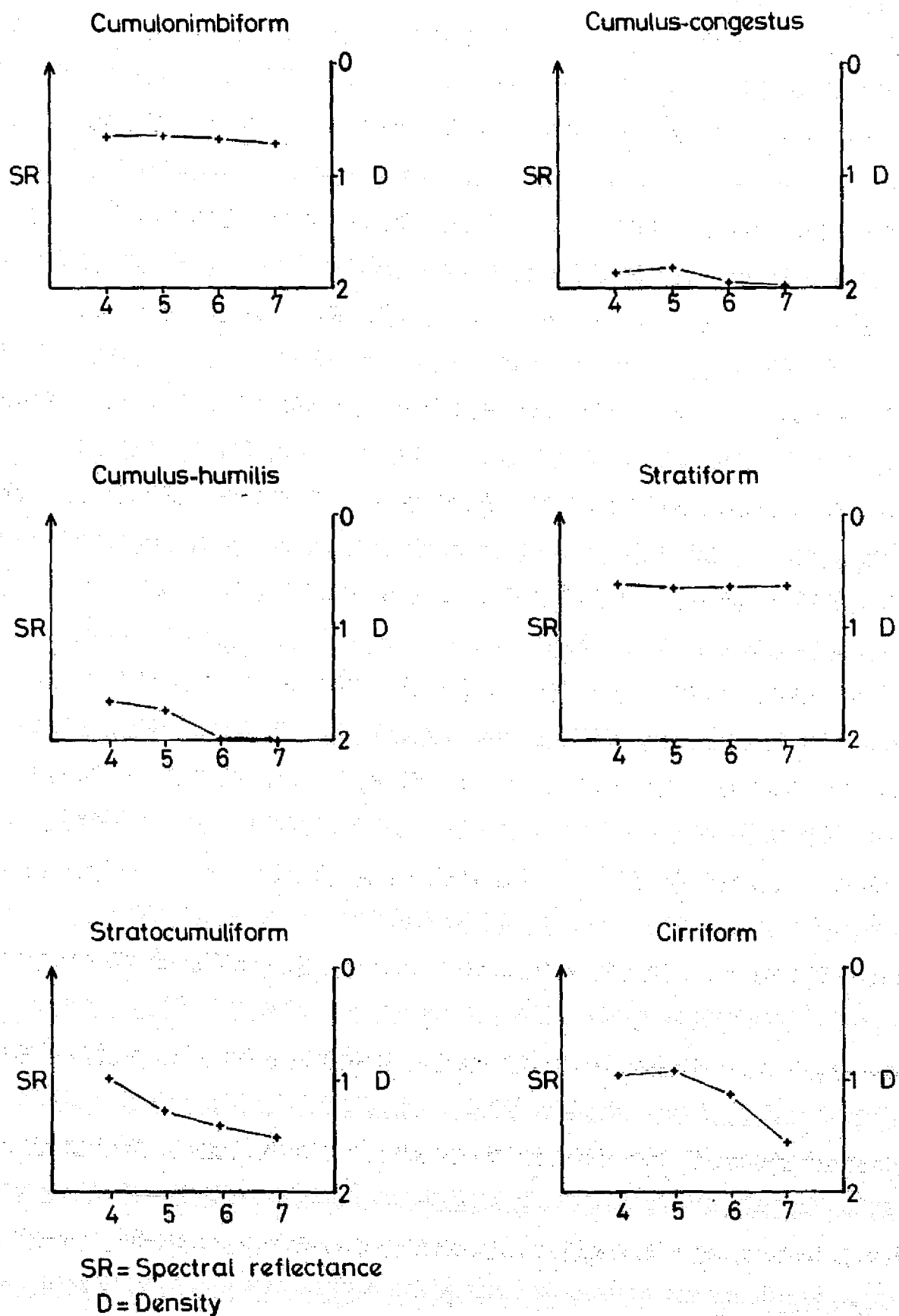


Fig. 6: Spectral Reflectance Graphs.

However, Folk and Ward (1957, p. 23) managed to produce a four-variate graph to represent the relationships between the four summary statistics in one diagram. Often, the analysis of such data has been extended by using clustering and discriminant analyses as classification procedures to allow new data values to be assigned correctly to previously determined groupings.

It is felt that this latter type of analysis may prove most useful in attempts to assign new cloud information in Landsat data to previously determined cloud types, defined in terms of their moment statistics. However, some problems would have to be solved before this were to be possible. For example, our results for stratiform clouds indicate that the application of such techniques to non-normally distributed data without some prior transformation can lead to misleading, possibly erroneous, results and conclusions. One solution might be to transform the data after initial statistics had been calculated. For example, Folk and Ward (1957) produced a transformed kurtosis statistic ( $K'$ ) derived from the ordinary kurtosis value, ( $K$ ). The relationship is as follows:

$$K' = \frac{K}{(K + 1)}$$

If this transformation had been applied in our study, the range of kurtosis values would have ranged from about 0.5 to 1.0, much less than the range we found. This transformation produces an approximately normal kurtosis distribution (Folk and Ward, 1957, p. 15).

A further problem with our distributions is that at the brightest end of the scale they are "open-ended": no lower limit was defined. Folk (1965), in discussing grain size analyses of sediments, felt that the application of the method of moments to such open-ended distributions might not be justified. This may be pertinent to our extreme results for stratiform clouds, where likely saturation of the image caused many values to be located in the unbounded step 1 of the grey-scale step-wedge.

It is apparent, therefore, that considerable work remains to be done if a worthy aim is to produce an operational cloud identification scheme for Landsat-type imagery based on cloud brightness statistics. However, the difficulties should not prove insurmountable if careful thought is given to experimental design and operation.

## IV

ACCOMPLISHMENTS

Analysis of sample multispectral images for six different categories of clouds have revealed marked differences between the reflectance characteristics of clouds and cloud fields or cloudy areas in the visible/near infrared region of the electromagnetic spectrum. Although the results obtained so far relate only to clouds imaged over coastal waters of the British Isles in summer the method by which the results were obtained could be applied quickly and cheaply to the analysis of further images.

## V

PROBLEMS

Several problems of note were encountered in this stage of our ERTS Follow-on Programme Study. These included:

1. Processing problems

These were of two different kinds, namely those already discussed at some length related to evident variations in the processing of Landsat imagery by NASA, and those related to the equipment available to us for image analysis. The two are interconnected in the sense that the poor quality of the copy negatives provided by NASA (see Barrett and Grant, 1975a p.8 ) determined that we should use the 70 mm positive transparencies obtained from the same source for the microdensitometry investigation, despite their small size for this purpose, rather than enlarged positive transparencies generated from our archive of 70 mm negatives. Since the Optronics Photoscan has a limited number of spot



sizes for image analysis our unit areas represented a larger area on the ground than we would have liked.

## 2. Interpretation problems

It did not appear that we could satisfactorily disentangle the different and variable influences of picture processing and cloud characteristics in order that we might, with reasonable confidence, assess the cloud differences for their statistical significance. Consequently we have expressed our interpretation of our results only in qualitative terms.

## 3. Schedule problems

In view of the wide-ranging nature of our project we may be unable to devote as much time to the theme of this report as its theme deserves. However, we hope to apply the methods developed here to some further images for two purposes:

- a) To obtain further information on the relations between the unit sizes of the areas measured by the microdensitometer and the brightness characteristics of the clouds and cloudy areas; and
- b) To test the similarity between such brightness characteristics for similar cloud fields viewed under contrasting solar illumination conditions, e.g. around the summer and winter solstices.

## VI DATA QUALITY AND DELIVERY

Our inability to produce useful positives from the 70 mm negatives received from NASA continues to affect our work adversely. Test positives developed from these negatives have been of a lower quality than those we have produced by copying the 70 mm positives onto contact negatives and then developing these. We are not sure why this should be the case.

Delivery of imagery seems to have slowed further as our project

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period has passed. We are still awaiting imagery for March 1976 at the time of writing (mid-August 1976). This has had some effects upon the sequence of work in our study; some of these effects were alluded to in the Introduction to this Report.

## VII RECOMMENDATIONS AND CONCLUSIONS

Although the assessment of the brightness characteristics of clouds imaged multispectrally by Landsat is a worthy topic of enquiry in its own right, much of our interest in this matter stems from our broader work in the Applied Climatology Laboratory of the Department of Geography in the University of Bristol. This is concerned with the search for an automatic (objective) method for cloud image analysis and cloud recognition, in relation to a wide range of potential areas of application. The most direct methods of objective cloud mapping include:

- a) Brightness contour mapping, as practised with both visible and infrared imagery in the Applications Branch of the National Oceanic and Atmospheric Administration, Camp Springs, Md.;
- b) Brightness/texture analysis, a basis for which has been developed in this Department (Harris and Barrett, in preparation);
- and c) Multispectral image analysis, summarised by Shenk, Holub and Neff (1976).

The first of these would be difficult to develop into an operational cloud recognition method because of the ambiguity which is evident in contour maps prepared from either visible or infrared imagery when relationships between image brightness and cloud type are considered. For example in visible imagery moderately thick low to middle level stratified cloud may be difficult to distinguish from thick alto- or even cirrostratus; these cloud types (and others) all reflect incident radiation strongly. In infrared imagery deep convective cloud can give brightness

temperatures as low as those associated with deep layered cloud. At best such a method would be an enhancement technique associated with which there would have to be some qualitative assessment of the brightness contours in terms of cloud types.

The second is much more attractive in that it employs two criteria rather than one for the objective differentiation of cloud type. Initial tests suggest that brightness/texture distributions for broad areas of cloud can be subdivided quite well into different cloud categories by discriminant analysis. The chief disadvantage of such a method arises from the common sampling method, which subdivides the initial data array into sub-arrays (say 5 x 5 or 6 x 6 picture points apiece) in order that texture measures might be made: texture is essentially a field characteristic, not a point characteristic as is the case with picture brightness. One significant consequence of this is that some of the resolution of the original data is sacrificed in brightness/texture analyses, on which cloud recognition depends. Even then some cloud types may be hard to separate, especially deep, widespread stratiform/layered cloud and large convective cloud masses topped by dense anvils of cirrus.

The third possibility would appear to have an advantage over the first in that a number of cloud responses would be available for each picture element, increasing the possibility that worthwhile cloud identification could be based thereon. It would also appear to have an advantage over the second in that the full spatial resolution of the original picture information obtained from the satellite could be used for cloud mapping and recognition. However, the present Landsat MSS is not ideally suited for such an operation because of the narrowness of its coverage of the visible-infrared region of the electromagnetic spectrum: the addition of a channel in the broad atmospheric window waveband in thermal infrared (as planned for Landsat C) should significantly help to differentiate further the spectral signatures for different categories of cloud; the addition

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of a further channel deeper into the infrared region (c. 20-23  $\mu\text{m}$ ) might help still more, especially in differentiating between deep layered clouds and cumulonimbus topped by thick cirrus varieties. In their earlier work Barnes and Chang (1968), Greaves and Chang (1970) and Lo and Johnson (1971) concentrated upon rather low resolution weather satellite data when seeking to assess the possibilities of multispectral cloud type identification procedures. Similarly Shenk and Holub (1973) and Shenk, Holub and Neff (1976) based their conclusions on MRIR analysis, and admitted that their proposed Cloud Type Decision Matrix might be expected to work well without further assistance and/or refinement only over tropical oceans. We would like to think that some future satellite system might employ a multispectral sensor system with a daily, global mapping capability and a resolution more in keeping with the present Landsat MSS than the Tiros or Nimbus MRIR - but designed for simultaneous Earth observation/atmospheric assessment purposes. It is probably only in this way that a multispectral cloud identification system could be operated economically in the foreseeable future - economy of effort as well as cost being significant when it is remembered that a brightness/texture cloud identification scheme is well within the realms of practical possibility, this suffering chiefly by comparison on account of the resolution problem.

It would seem that considerable benefits might accrue to all concerned were atmospheric and terrestrial investigators to collaborate more closely in future satellite design and operations: the problems of meteorologists, oceanographers and Earth resource scientists are, perhaps, not only more closely interrelated than is commonly acknowledged, but more amenable to solutions which overlap considerably even though they might not precisely coincide.

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